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## Teaching Neuroanatomy Virtually: Integrating an Interactive 3D E-Learning Resource for Enhanced Neuroanatomy Education

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A thesis submitted in partial fulfillment of the requirements for the degree in Doctor of Philosophy

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## Abstract

An interactive 3D e-learning module was developed to complement neuroanatomy instruction in both an undergraduate medicine neuroanatomy laboratory course, and an undergraduate systemic human anatomy course. The 3D e-learning resource provided students the opportunity to manipulate a dynamic 3D model to view structures from any desired angle, view deep cortical structures at high magnification, and add interactive structural labels. A randomized cross-over design was utilized to separate participants into two groups. Each group completed baseline anatomy knowledge and spatial ability knowledge assessments, followed by access to either the 3D e-learning module or conventional learning resources. Participants completed a post-module anatomy knowledge assessment prior to accessing to the other learning modality. A final post-module knowledge assessment was administered following student exposure to the second learning modality.

Students who initially accessed the 3D module scored significantly higher on the post-module knowledge assessment than the students who initially accessed the conventional anatomy resources. Participants who accessed the 3D learning resources following gross anatomy resources, significantly improved on the final post-module knowledge assessment. A negative correlation was observed between spatial ability and change in assessment score following access to the 3D module suggesting that students with low spatial ability experienced a greater positive effect on their learning of neuroanatomy following the use of the 3D learning module than students with higher spatial ability.

A novel virtual syncretion assessment was also developed that assessed participants' ability to place neuroanatomical structures in a partial 3D neuroanatomical model, rather than a conventional nominal response. Participants who initially utilized the 3D e-learning resource performed significantly better on the virtual syncretion assessment than participants who initially utilized the 2D e-learning resource. Participants who accessed the 3D e-learning resource subsequent to the 2D e-learning resource significantly improved their performance on the final virtual syncretion assessment. Results of this

study could be used to inform the effective development and implementation of 3D e-learning resources to improve neuroanatomy instruction, particularly for students with low spatial ability.

## Keywords

neuroanatomy education, medical education, e-learning, three-dimensional modeling, cognitive load, spatial ability, virtual syncretion

## Co-Authorship Statement (where applicable)

The written material contained in this thesis is the original work of the author. Lauren K. Allen participated in all aspect of the work contained within this thesis including the development and design of the 3D e-learning resource, 2D e-learning resource, conception of the research questions, collection and analysis of data, and preparation of the manuscripts. The roles of the study's co-authors are detailed below:

### Chapter 2: Development of an Interactive 3D E-Learning Resource for Enhanced Neuroanatomy Education

The manuscript detailing the technical development of the 3D e-learning resource is published in the journal *Studies in Health Technologies and Informatics*. The preliminary empirical evaluation of the 3D e-learning resource is published in the journal *Anatomical Sciences Education*. All authors on the manuscript shared in the conception of this research study. L. Allen, with use of a subset of images from the Visible Human Project dataset, developed the 3D structural representations contained within the brain model. The data for this study was collected, analyzed, and interpreted by L. Allen with inputs from Drs. de Ribaupierre and Eagleson. Composition of the manuscripts was performed by L. Allen with guidance from Drs. de Ribaupierre and Eagleson.

### Chapter 3: Evaluation of the Impact of the 3D E-learning Resource on Neuroanatomy Learning Outcomes

Conception of this research study was shared by L. Allen and S. de Ribaupierre. The data for this study was collected, analyzed and interpreted by L Allen. The preparation of the manuscript is being carried out by L. Allen with inputs from Drs. de Ribaupierre and Eagleson. The manuscript will be submitted to the journal *Medical Education*.

### Chapter 4: The Influence of Spatial Ability on Learning Spatial Neuroanatomy.

Conception of this research study was shared by L. Allen and S. de Ribaupierre. The data for this study was collected, analyzed and interpreted by L. Allen. The preparation of the manuscript is being carried out by L. Allen with inputs from Drs. de Ribaupierre and



Eagleson. The manuscript will be submitted to the journal *Anatomical Sciences Education*.

#### Chapter 5: The Impact of Spatial Ability on Interactions with E-Learning Resources.

Conception of this research study was shared by L. Allen and S. de Ribaupierre. The development of the technical modifications and enhancements to enable the deployment of the e-learning resource on a web platform, was completed by L. Allen and T. Wright. The development of a web server and database for the collection of user data was completed by L. Allen, T. Wright, and K. Brightwell. The data for this study was collected, analyzed and interpreted by L. Allen. The preparation of the manuscript is being carried out by L. Allen with inputs from Drs. de Ribaupierre and Eagleson. The manuscript will be submitted to the journal *Anatomical Sciences Education*.

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## List of Abbreviations

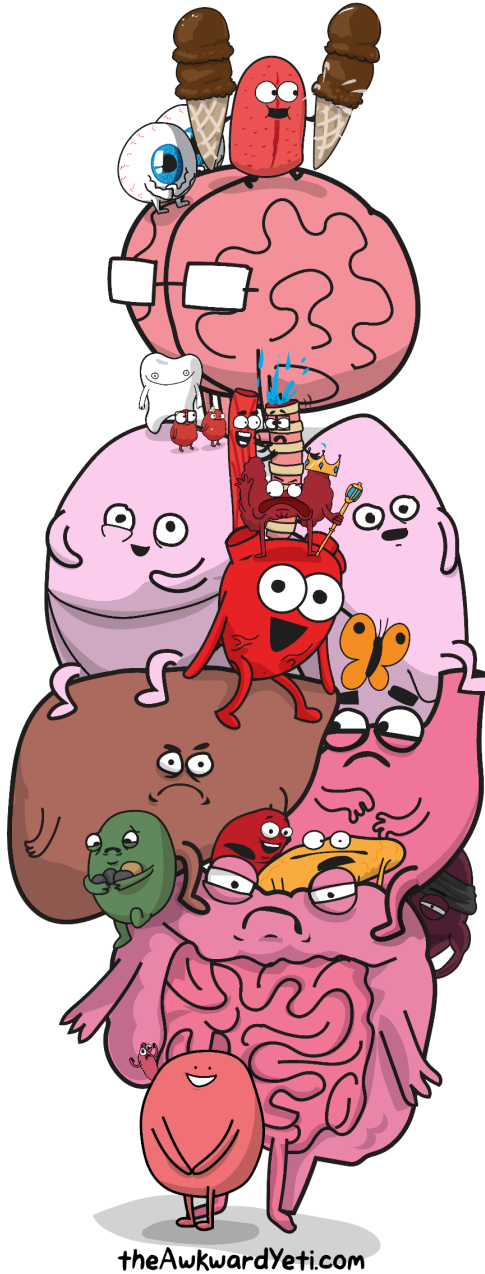
1. Science, Technology, Engineering, Mathematics, and Medicine (STEMM)
2. Three-Dimensional (3D)
3. Two-Dimensional (2D)
4. Electronic Learning (E-Learning)
5. Cognitive Load Theory (CLT)
6. Working Memory (WM)
7. Long-Term Memory (LTM)
8. Spatial Visualization (Vz)
9. Spatial Orientation (SO)
10. Spatial Relations (SR)
11. Closure Speed (CS)
12. Flexibility of Closure (CF)
13. Santa Barbara Solids Test (SBST)
14. Mental Rotations Test (MRT)
15. Verbal Working Memory (VWM)
16. Visuospatial Working Memory (SWM)

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## Preface

“Learning is a treasure that will follow its owner everywhere” - Chinese Proverb



Creator: Nick Seluk  
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## Chapter 1

# 1 Literature Review: The Evolving Status of E-Learning in Higher Education

This chapter outlines the evolution and impact of e-learning technologies in post-secondary education particularly in the science, technology, engineering, mathematics and medicine (STEMM) disciplines, as well as the transformation of anatomy curricula and pedagogies, the incorporation and evaluation of e-learning technologies in anatomy curricula, and principles of Cognitive Load Theory (CLT) as they relate to informing the effective design of e-learning materials. It will also examine how individual differences in spatial ability may impact learning of visually complex information, and the potential to modulate differences in spatial ability to facilitate learning.

## 1.1 Incorporation of E-Learning Resources in Postsecondary Education

### 1.1.1 The Rapid Evolvment of E-Learning Technologies

The educational landscape has experienced a significant period of change as a result of many advancements in digital technologies, including online course platforms, 3D visualizations, and virtual reality simulations. These technological innovations have dramatically influenced the methods for teaching and learning across science, technology, engineering, mathematics and medicine (STEMM) disciplines, including the anatomical sciences ( Leung et al. 2006; Johnson, Charchanti, and Troupis 2012; Trelease 2016). E-learning is an increasingly popular and broad term that encompasses many different teaching and learning strategies, and may be defined as instruction that is delivered to students on a digital device, including a smartphone, computer, or tablet (Clark and Mayer 2011). Apparent advantages of e-learning resources include the fluid nature of the resources, which are readily modifiable in order to customize the content presented to different student groups, as well as greater accessibility as these resources are available to students at a time and location of their choosing rather than being limited to a predetermined time and physical location. Specifically, in the anatomical sciences



education, e-learning offers additional advantages when compared to the traditionally employed laboratory resources, which often include cadaveric specimens and physical models. With the increasing enrolment in undergraduate anatomy courses, the cost of maintaining a sufficient number of physical models or preparation of cadaveric specimens is becoming increasingly prohibitive (Nicholson et al. 2006; Preece et al. 2013; Dissabandara et al. 2015). Cadaveric specimens also require significant resources to ensure their safe and effective storage, in order to maintain the integrity of the specimens, and to ensure the safety of students and educators. Conversely, e-learning resources enable increased versatility and safety over conventional tools as they are adaptable, reusable, and do not pose any safety or risk of disease transmission to students during their learning interactions.

E-learning instruction may be delivered synchronously, during which time the teachers and students engage simultaneously in a virtual lesson or tutorial, whereas asynchronous e-learning is a more student-centered approach that utilizes e-learning technologies to enable the sharing of learning resources with students at their chosen time and pace. The format of e-learning resources facilitates the opportunity of multimedia learning and may include combinations of text, static images and dynamic models or animations. Multimedia learning occurs when students form mental representations from the combination of both words (spoken or printed text) and pictures in the format of drawings, photographs, animations or videos (Mayer 2005). Results have shown the combination of words and corresponding images enables improved retention and transfer of information in comparison to learning from words alone, an effect termed the multimedia principle (Mayer and Moreno 2002).

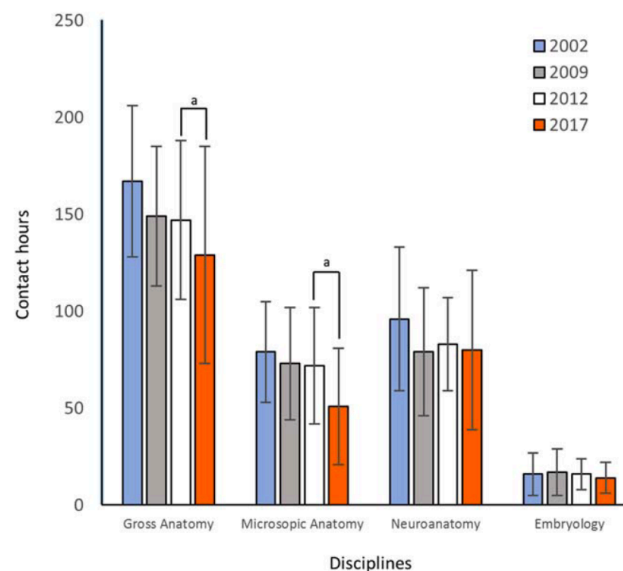
Recent trends in post-secondary education have demonstrated an increasing demand for online learning opportunities that has driven growth in the e-learning sector, leading it to become one of the fastest growing learning modalities globally (Allen et al. 2015; Docebo 2016). Consequently, investments have been made in an effort to optimize the potential success of e-learning resources. In the European Union (EU), a High Level Group on the Modernization of Higher Education has been established with a mission to improve the quality of delivery and learning outcomes associated with post-secondary e-

learning. As teachers' skills and willingness to use educational technologies shape the courses currently available, most courses presently retain a conventional, linear teaching design. Recommendations stemming from the EU's Modernization of Higher Education report include providing additional institutional support for teachers to facilitate their skill development, to maximize the advantages afforded by e-learning technologies and improve the quality of learning for their students (McAleese et al. 2013). A recent investigation of the education trends in Canadian postsecondary institutions reported 93% of Canadian universities offer online courses and programs, with 29% of all postsecondary students enrolled in at least one online course (Bailey 2015). In Ontario specifically, the provincial government has invested 42 million dollars between 2014 and 2017 towards the establishment of high quality post-secondary courses. With enrolment in online courses anticipated to continue rising at Canadian postsecondary institutions and globally (Bailey 2015), it is essential that the design of e-learning resources is guided by educational theories to maximize the education potential of this emerging modality, and optimize students' learning experiences and outcomes.

### **1.1.2 Curricular Reform in the Anatomical Sciences**

Historically, cadaveric dissection has been an integral component of teaching and learning anatomy (Collins et al. 1994; Drake, Lowrie, and Prewitt 2002; Drake 2014). In the early twentieth century, anatomy was a central component in the undergraduate medical curricula, and accounted for approximately twenty percent of instructional time, amounting to over 800 hours dedicated to anatomical instruction through a combination of lecture and cadaveric laboratory formats (Eldred and Eldred 1961). Following the release of the Flexner report in 1910, widespread transformations began with the recommendation for the separation of preclinical and clinical studies (Flexner 1910). The implications of this report were substantial, including a negative trend in instructional time devoted to anatomy education. Significant reform occurred again in the late twentieth century, as a new shift in pedagogies began towards an integrated multi-subject approach, as opposed to the single-subject approach that had traditionally been favoured (Drake et al. 2009). Advancements in educational and medical technologies have had a profound effect on teaching methods in the medical sciences, both in the classroom and

the clinic, by which future health professionals are trained during their undergraduate education. As shown in Figure 1, a recent survey of the anatomical programs at postsecondary institutions reports the total number of class hours was on average 129, with an average of 51 hours dedicated to classroom lectures and an average of 76 hours devoted to instruction in the laboratory (McBride and Drake 2018). While trends in anatomy curricula hours have shown a consistent decline since 1973, it has been suggested that course hours may be approaching a plateau over recent years, due in part to concerns that further decreases in laboratory hours would be detrimental to student learning outcomes (Drake et al. 2009).



**Figure 1: A recent survey of the changes in contact hours included in anatomical programs at postsecondary institutions reports a decline in most anatomical disciplines. In 2017, the total number of class hours for gross anatomy was on average 129 hours, with an average of 51 hours dedicated to classroom lectures and an average of 76 hours devoted to instruction in the laboratory (McBride et al. 2018)**

An extensive combination of factors is driving reform in academic medicine, including but not limited to decreased teaching hours, lack of cadaveric teaching resources, and increasing demand from students to study and learn remotely (Murgitroyd et al. 2015). As anatomy courses continue to integrate basic science and clinical concepts, electronic educational materials could be utilized to provide students with alternate resources that provide new opportunities to enhance learning not previously afforded by using traditional learning resources. The prevalence and promise of emerging e-learning technologies has prompted educational institutions to integrate emerging educational technologies in an effort to transform their pedagogical practices and meet the evolving educational needs of 21<sup>st</sup> century students. As new educational technologies emerge, it is imperative that their designs incorporate principles of educational psychology to facilitate learning, and the effects of their integration into curricula are evaluated to ensure a positive impact on learning outcomes.

### **1.1.3 Impact of 3D resources on learning outcomes**

Until the late 20<sup>th</sup> century, the format of anatomy education had remained largely unaffected, and unenhanced by advances in educational technologies (Sugand, Abrahams, and Khurana 2010). Instead, it remained predominantly dependent on conventional foundations including printed textbooks, didactic lectures, and cadaveric laboratory resources (Trelease 2016). As the prevalence of e-learning resources integrated into STEMM curricula continues to increase, the transformation of education strategies has dictated a growing need for the evaluation of the impact of such learning tools on student learning outcomes. Such evaluations have been approached both quantitatively as measured by performance on written and practical assessments, as well as qualitatively through the evaluation of students' perceptions and satisfaction with the addition of new e-learning resources into their curricula. A recent review of technology-enhanced learning in anatomy examined the overall trends in the findings of studies evaluating the impact of technology-assisted learning experiences, and found the majority of evaluations of e-learning technologies have focused on qualitative aspects of success (Clunie et al. 2017). While many new technologies are favourably perceived by students, it is crucial that quantitative evaluation also be performed to ensure the increased student satisfaction

translates into improved learning.

Developing spatial anatomy knowledge is a process that requires time and is best achieved through active learning exercises, which may be achieved in a physical laboratory setting or by using interactive e-learning resources (Heylings 2002). While learners may be able to sufficiently acquire knowledge from an anatomical text to answer nominal multiple-choice questions, their spatial knowledge may be found to be deficient when required to answer spatial knowledge questions or perform practical examinations. Given the visually complex nature of anatomy, the inability to visualize a given structure is frequently reported by students who have difficulty identifying structures during clinical examinations (Heylings 2002; Tam et al. 2009). Inconclusive findings have suggested that access to 3D models may provide the additional support and opportunity needed by students to develop the ability to visualize complex anatomical structures and relationships. Novel anatomy applications are playing an increasingly important role in medical education by allowing students to visualize and manipulate structural and spatial relationships with the use of 3D models, that were not readily discernable from traditional resources (Lewis et al. 2014). A key strength is the ability to consolidate and present the information in multiple modalities, in order to present the information to the learners in such a way that it meets their learning styles and strengths.

Some past studies have sought to measure the efficacy of 3D anatomy resources exclusively through qualitative assessment. An example in area of vascular anatomy reported that interactive 3D stereoscopic models of both healthy and pathological aortic anatomy were perceived by students to be advantageous to their learning when compared to current curricula, which included both lecture-based and cadaveric laboratory instruction (Brown, Hamilton, and Denison 2012). Similarly, an interactive 3D model of the anterior forearm musculature was quantitatively and qualitatively assessed for its effectiveness as a learning resource. The 3D learning tool was found to be an equally effective teaching tool, as assessment scores were equivalent for students who learned the information with either traditional or 3D e-learning resources. A limitation of this study was the lack of description or evaluation of traditional resources to which the 3D resources were compared, which may have influenced the results. Qualitatively, students

provided positive feedback on the 3D learning tool, and thought it would serve as a valuable addition to complement their existing medical curriculum.

Other studies concentrated on evaluating the quantitative effects of 3D models on assessment scores have found positive effects of learning performance. When students were provided with a web-based tutorial of the ear that included an interactive 3D model, their knowledge of 3D relationships was significantly better than students who accessed the same web-based tutorial without the addition of the 3D model (Nicholson et al. 2006). Similar positive results were observed in an interactive 3D model of temporal bone anatomy, which measured the effect of the incorporation of a 3D model into the conventional anatomy tutorial. When the web-based 3D model was provided as an adjunct to a lecture-based course for medical residents, students' performance on the final examination was significantly better than those who were not provided access to the 3D resource. In addition, students viewing the resource perceived it as helpful in improving both their anatomical knowledge and ability to perform surgical skills (Venail et al. 2010a).

#### **1.1.4 Guiding Principles of Cognitive Load Theory for Effective Design of E-Learning Resources**

Effective learning requires the co-ordination of cognitive, affective, social, environmental and metacognitive processes to successfully acquire and integrate new information into existing schema or mental representations (Young et al. 2014). Research in educational psychology suggests that the effectiveness of any instructional tool is dependent upon how well its design reflects the underlying cognitive architectural structures controlling the processes essential for learning to occur (Clark and Mayer 2011; Mayer 2010).

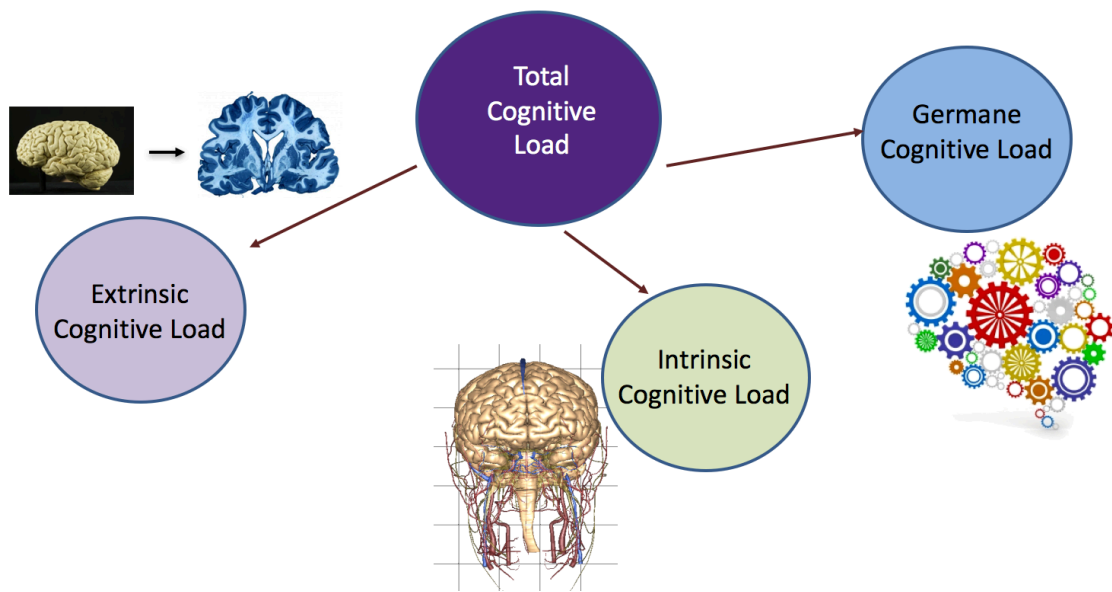
Cognitive Load Theory (CLT) is a prominent cognitive-based learning theory (Sweller, van Merriënboer, and Paas 1998), which is increasingly receiving attention in medical education, and places emphasis on memory systems, learning processes and aspects of cognitive load, as essential components that must be considered and controlled to develop effective learning environments. CLT is of high relevance for medical education specifically as the conceptual and procedural knowledge to be learned by novice students has a high level of complexity and often requires the integration across several topics or

courses. Many students experience difficulty mastering the complex concepts and skills introduced during their training for allied health professions, and CLT provides an explanation for why this may be occurring, as well as providing framework for approaches to instructional design that may be effective in reducing cognitive load, and improving student learning.

Information from one's environment enters the mind through a sensory memory system, that has a large capacity for visual and auditory information, but only retains the information for a very short period of time. Processing and filtering of this sensory information is a process through which only a small portion of this information enters conscious awareness, and is processed by working memory (WM), in order to avoid overloading due to the volume of information being received from an individual's environment. The primary function of the WM systems is to organize information into mental representations or categories to be stored in long-term memory (LTM), which may be retrieved and referenced to infer or deduce patterns and relationships between stored knowledge and new information encountered in future interactions. While it is thought that both sensory memory and LTM have an infinite capacity, the cognitive structures involved in WM are only capable of holding 5-7 separate units of information for a very brief duration at any given time (Miller 1955;Mayer, Heiser, and Lonn 2001). The limited capacity of WM provides a potential justification for the "Doorway Effect", a term reported in cognitive psychology to describe the disruption of memory by a change in location. The "Doorway Effect" is thought to be a consequence of the limited capacity of WM, that is may not be able to process new information about the change in location, and simultaneously retain other information in WM, causing one to forget information such as the question they planned to ask prior to passing through a doorway. The limited capacity of WM has a profound impact on student learning in the allied health sciences, as many learning tasks involve the understanding of more than 7 units of complex spatial, conceptual, or procedural information. In order to be successful despite the inherent limitations of WM, students must effectively organize and process information into mental representations known as schema, and connect these representations with related prior knowledge, a process which may impose a high level of cognitive load. Cognitive load is a multi-faceted concept that explains the burden placed on cognitive architecture

during learning, and may be sub-divided into three distinct components: intrinsic cognitive load, which is the degree of difficulty imposed on WM by the content of the task, whereas extrinsic cognitive load is the burden on WM imposed by the methods and techniques used in the organization and presentation of education information, and germane cognitive load is the effort required by WM to process the incoming information, as shown in Figure 2. As intrinsic and extraneous aspects of cognitive load are additive, when situations impose a high intrinsic cognitive load, the introduction of further extraneous cognitive load may interfere with learning processes. While intrinsic cognitive load is relatively fixed, CLT suggests that effective design of instructional materials can decrease the levels of extrinsic and germane cognitive load, allowing for more WM resources to be devoted to processing the intrinsic cognitive load, and thereby improving learning outcomes. CLT describes that instructors may improve the design of their instructional material by organizing or “chunking” the information into smaller portions, in order to facilitate students’ organization of new information, and prevent the limited capacity of WM from becoming overloaded by incoming information.





**Figure 2: Overview of the subcomponents that cumulatively account for the cognitive load placed upon individuals while completing a task. Cognitive load may be subdivided into 3 distinct components intrinsic cognitive load, which is the degree of difficulty imposed on WM by the content of the task, whereas extrinsic cognitive load is the burden on WM imposed by the methods and techniques used in the organization and presentation of education information, and germane cognitive load is the effort required by WM to process the incoming information. (Image associated with extrinsic cognitive load: <http://360anatomy.uwo.ca/>; Image associated with germane cognitive load: <https://www.forbes.com/site/siimonreynolds/2013/04/02/is-complexity-ruining-your-business/>)**

A second principle described by CLT as beneficial for learning is the multimedia principle, that explains learning is enhanced when the information is presented using words and graphics instead of words alone. The co-ordination of words and graphics is thought to have a beneficial impact on learning, as it promotes active learning and increased engagement. As a result, learners are more likely to develop mental representations that involve both the words and graphics, and by doing so form connections between the pictorial and verbal information. Conversely, presenting information in a singular textual format, may encourage learners to engage in shallow learning processing, with fewer connections formed between the words and pre-existing knowledge (Clark and Mayer 2011). Furthermore, the elimination of any non-essential graphic or textual information, also known as the coherence principle, also helps to minimize distractions experienced by the learner. When incorporated into instructional design, this removal of superfluous information reduces extraneous cognitive load, and thereby helps to avoid an overload of WM capacity and support effective learning.

Additionally, results have demonstrated people are able to learn more deeply from a multimedia resource, when visual cues are added to emphasize the organization and important characteristics of the essential material, a feature referred to as the signaling principle. The rationale behind the signaling principle explains that the efficiency of the learning process can be improved if the instructional design of learning material directs the learners' attention to the most important information. This strategy assists with reducing learner distraction and facilitating the development and organization of mental representations of the information presented. Signaling of verbal material may be achieved by creating outlines, heading, and pointer words, whereas signaling of visual material may be accomplished through highlighting, spotlighting, or the addition of arrows (Mayer 2005).

Evidence has also shown that learning may be improved by presenting text and graphics in a closely integrated formation, as compared to displaying the information separately, a principle known as the contiguity principle (Mayer 2005). The concept of spatial contiguity recommends that corresponding graphics and text should be located in close proximity to each other on the screen in e-learning materials. Alternatively, text for a

corresponding graphic may be interactive with the addition of mouse-rover or roll-over text, that only appears adjacent to the graphic when the mouse touches a specific portion of the image. It has been shown that students' learning of cardiac anatomy significantly improved when text appeared near the related part of the graphic being described (Erhel and Jamet 2006). A systematic review also reported strong support for the educational benefits of spatial contiguity of graphics and text, with a medium overall effect size of 0.72 (Ginns 2006).

Human cognitive architecture is the foundation for the CLT, that seeks to explain the many components involved in different aspects of memory formation and the process of learning through the formation and organization of schema in WM. This theory draws attention to the limited capacity of WM, and the challenges experienced when novice learners attempt to develop an understanding of complex information such as in the anatomical sciences. In situations that place a high cognitive load burden on a students' WM, the capacity of the cognitive systems involved may be exceeded, and thus the successful acquisition of new knowledge may be limited. The evaluation of instructional techniques and design strategies that focus on reducing the amount of extraneous cognitive load have been shown to facilitate improved learning across a wide range of topics and subjects (Grunwald and Corsbie-Massay 2006; Qiao et al. 2014). While continued research is required to evaluate the impacts of incorporating e-learning technologies into anatomical curricula, it is essential that these empirical results inform the design and deployment of emerging educational technologies in the most efficacious manner in order to maximize the training of future allied health professionals.

## **1.2 “Neurophobia”: The Challenges of Teaching and Learning Neuroanatomy for Novice Students**

Recent studies have highlighted a prevalent difficulty in the understanding, and resulting fear of neuroanatomy among medical students and novice physicians, who often report their perceived knowledge in the subject to be the lowest out of several medical disciplines. Such difficulties have been shown to result in a lack of confidence in their ability to diagnose and treat patients who present with neurological concerns (Flanagan, Walsh, and Tubridy 2007; Fantaneanu et al. 2014; Mccarron et al. 2014). This reported

lack of knowledge and confidence in neurology among medical trainees has inspired the term in the literature of “neurophobia”, which has been reported globally by several studies evaluating trainees attitudes and perceptions (Youssef 2009; Giles 2010; Zinchuk et al. 2010; Fantaneanu et al. 2014; Shiels et al. 2017). As first reported by Jozefowicz, neurophobia is due to students’ inability to apply their knowledge of the basic sciences when they enter the clinical setting (Jozefowicz 1994). Recent studies estimate the prevalence of neurophobia to be between 47.5-50% among medical students and 36-41% of junior doctors (Kam et al. 2013; Matthias et al. 2013), while making neurological diagnoses was rated as moderately to very difficult by nearly half of participating medical students. Recent trends have also shown the number of new physicians entering the field of neurology is much lower in comparison to other specialties, with only a 1.7% growth in the number of U.S. residency applications and positions available in neurology, as opposed to an 11.6% increase in the area of family medicine, and 25.6% in internal medicine (National Resident Matching Program 2017). As the general population ages, concerns for the impact of neurophobia on patient care are being amplified by the increasing burden of neurological diseases on the health care system. A report released by the Canadian Institute for Health Information underscores the importance of effective training of health professionals in the clinical neurological sciences, as neurological conditions represent 9% of acute hospitalization cases, and 20% of patients receiving inpatient rehabilitations have suffered a neurological injury (Canadian Institute for Health Information 2007). It is of high importance to address the underlying issues contributing to neurophobia and ensure medical trainees’ knowledge and confidence of neurology increases in order to train physicians with sufficient knowledge in the clinical neurological sciences and ensure a high level of care is maintained for patients with neurological concerns.

Several factors are involved in the development of neurophobia, including the high degree of difficulty understanding the structural and functional complexity of neuroanatomy, as well as difficulties experienced by novice students in retaining their basic neuroanatomical knowledge as compared to other basic science topics such as physiology and immunology. A recent study employed Likert-style questionnaires to help distill the factors that may contribute to the perceived difficulties with neuroanatomy, and

categorized these factors as either intrinsic to the subject (anatomical terminology and spatial relationships), or extrinsic to the subject (lecture duration and access to learning materials). It was shown that a greater proportion of students perceive intrinsic factors as causes of their difficulty learning the subject (Javaid et al. 2018). A subsequent thematic analysis of student responses identified three main barriers to learning that included the complexity of the topic, the large amount of content, and the difficulty in visualizing neuroanatomical structures and their spatial relationships (Javaid et al. 2018). While anatomy education is currently experiencing a period of evolution and modernization, e-learning resources have the potential to improve teaching and learning in many topics, including neuroanatomy. The potential benefits of any educational tool, including e-learning resources, may vary depending on individual differences between students such as level of previous knowledge, learning styles and strengths, and spatial ability (Ruiz, Cook, and Levinson 2009). Additional research is required to determine when and how to integrate e-learning resources into neuroanatomy curricula to optimize students learning.

## 1.3 Spatial Ability

### 1.3.1 The evolving definition of spatial ability

Spatial ability refers to a multifaceted skill set that allows individuals to represent, transform, create and retrieve visual information from their environment (Linn and Petersen 1985). Pioneering work by Thorndike in 1921 refuted the previous singular theory of intelligence suggested by Spearman (Spearman 1904), and instead proposed the existence of multiple intelligences. This preliminary work in cognitive psychology served as the foundation for the theory of multiple intelligences, including spatial ability (Thorndike 1921). Spatial ability constructs have received considerable attention in education psychology research since the mid-1940's, however there has been considerable discrepancies and an evolution of the theories describing the factors and cognitive architecture necessary for the development of spatial ability skills. An early review by McGee concluded the existence of two main factors contributing to spatial ability, Spatial Visualization (Vz) and Spatial Orientation (SO) (McGee 1979). Vz is considered the ability to manipulate mental representations of objects without referencing one's own position, and may be measured by tests such as the Paper Folding task,

whereas SO is considered to be an individual's ability to perceive and infer the appearance of an object from different viewpoints. Spatial Perception was later described as a component of spatial ability with many close similarities to SO, and is defined as the ability to determine spatial relationships in relation to one's own body (Linn and Petersen 1985). A later analysis of the structure of spatial ability saw the addition of a third major factor termed Speeded Rotation, later known as Spatial Relations (SR) (Lohman 1988), an ability which may be measured by cognitive tests requiring participants to determine whether a given object is a rotated, or reflected version of the original object.

One of the most comprehensive reviews of the factors contributing to an individual's total spatial ability utilized the analysis of over 140 datasets in order to identify five distinct components of spatial ability, which in addition to Vz, and SR, saw the inclusion of Closure Speed (CS), Flexibility of Closure (CF), and Perceptual Speed (Carroll 1993). The CS component measures one's ability to access spatial representations in long-term memory when partial cues for specific mental representations are presented, whereas the CF factor involves the ability to detect sub-patterns within a larger, more complex pattern. Finally, the perceptual speed factor is characterized by the speed with which one is able to detect a pattern in a given situation when visual distractions are present. While factor analytic studies on spatial abilities have sought to provide a comprehensive understanding of the nature of spatial ability, the inconsistency among investigators has contributed to conflicting interpretations and terminology in the literature. Secondly, factor analytic studies do not consider dynamic spatial abilities and environmental ability, which serve an important role in recent spatial ability theories (Hegarty and Waller 2005).

A more recent addition to the factors of spatial ability is Dynamic Spatial Ability, which refers to perceptions involving moving objects, and is most commonly measured by digital tests such as relative arrival time, in which participants indicate which moving object will arrive at a target first (Yilmaz, 2009). Environmental ability on the other hand, requires the integration of spatial information from an individual's surroundings, and is considered important for the development of navigational skills.

Presently, several similar frameworks exist to categorize the previously identified components of spatial ability, with most composed of three common sub-skills of spatial ability; spatial perception defined as the ability to use one's orientation in 3D space to determine the spatial orientation of object, spatial visualization defined as the ability to recognize objects which have been transformed from their original position, and mental rotation defined as the ability to determine if an object has changed from its initial orientation or angle in space (Yilmaz 2009).

### 1.3.2 Individual differences in spatial ability

Across participants and environments, the right hemisphere has shown to play a dominant role during tasks requiring spatial processing skills (Vogel et al. 2003). Sex differences in multiple components of spatial ability have been well-documented in educational psychology research (Linn and Petersen 1985; Nordvik and Amponsah 1998; Yilmaz 2009; Reilly, Neumann, and Andrews 2017), with tasks measuring mental rotation ability showing the largest differences between males and females (Voyer et al. 1995; Voyer, Voyer, and Saint-Aubin 2017). Such differences may be influenced by differential activation of cortical regions, with male participants showing dominant activation in the right cortical hemisphere, whereas females showed no differences in activation across the left and right cortical hemispheres (Vogel et al. 2003).

Another theory postulated to account for the sex differences observed in spatial ability is prenatal exposure to androgens, with evidence to support that females with early exposure to androgens develop spatial abilities equivalent to males (Puts, Gaulin, and Breedlove 2007). Changes in spatial ability have been documented in individuals diagnosed with conditions affecting levels of androgens including congenital adrenal hyperplasia, which results in elevated levels of androgens prenatally, due to an enzyme deficiency responsible for an overproduction of adrenal androgens. Despite receiving treatment as infants, studies have found females with congenital adrenal hyperplasia display masculinized spatial abilities congruent with average male scores for spatial intelligence (Hampson, Rovet, and Altmann 1998; Vuoksima et al. 2010; Berenbaum, Korman Bryk, and Beltz 2012). Additionally, female twins with male co-twins have also been shown to exhibit increased spatial ability, with the hypothesis that it may be

attributable to greater exposure to androgens in utero produced by their male twin (Vuoksima et al. 2010). Conversely, conditions in which androgen and estrogen levels are depleted, as in Turner Syndrome, females exhibit deficits in spatial ability scores, when compared with others unaffected by the disorder (Nijhuis-van der Sanden, Eling, and Otten 2003).

A recent review has reported spatial ability is also influenced by participant age, with age-related effects reported on the performance of a wide variety of spatial tasks (Techentin et al. 2014). Age-related effects in the performance of many cognitive domains, and specifically spatial cognitive tasks have been documented in previous students, with many findings showing a negative correlation between age and spatial ability (Techentin et al, 2014) as quantified by decreased accuracy by adults of advanced age while completing spatial tasks such as the Block Design Task (Paulo et al. 2011), and the short Object Perspective-Taking Task (Borella et al. 2014). While participants between the ages of 20 and 40 performed well on the short Object Perspective-Taking Task, visual spatial skills began to decline at the age of 40, with the declines becoming more dramatic after the age of 60 (Borella et al. 2014).

These findings provide support for the potential role of biological factors such as gonadal hormones in the developmental differences in spatial abilities between the males and females. Implications of sex differences in spatial ability have been investigated due to the connection between spatial ability levels and skill acquisition (Clem et al. 2010; Kwant et al. 2015; Abe et al. 2017), knowledge acquisition of spatial information (Richardson, Montello, and Hegarty 1999), and performance in science, technology, engineering, mathematics and medicine (STEMM) disciplines requiring the knowledge and understanding of spatially complex topics (Wai, Lubinski, and Benbow 2009; Lufler et al. 2012; Uttal and Cohen 2012; Nguyen et al. 2014).

### **1.3.3 Malleability of Spatial Cognitive Skills**

There have been several studies conducted to investigate whether training may reduce individual differences in spatial ability, resulting in the improved performance of low spatial ability individuals in fields requiring knowledge of complex spatial knowledge



such as chemistry (Carlisle, Tyson, and Nieswandt 2015), engineering (Sorby 2009), and anatomy (Guillot et al. 2007; Hoyek et al. 2009). A review of the literature investigating the malleability of spatial skills as a result of spatial training found an average effect size, or magnitude of the difference between the control vs spatial training group, reported an effect size of 0.47, suggesting that spatial skills are influenced by both training and environmental events (Uttal et al. 2013). The stability of changes to spatial cognition has also been shown to be durable over time, with the no significant differences observed in the strength of training effects immediately following training events, or with evaluations conducted up to one month following training (Uttal et al. 2013), although further research is warranted to determine the durability of spatial ability skills over longer time periods. The impact of cognitive training may also induce biological changes in neural systems involved with spatial tasks, as improvements have been shown to be associated with differences in neural activity in neural structures associated with learning of spatial information including the hippocampus and parahippocampal gyrus (Hötting et al. 2013).

Evidence supports a reciprocal relationship between educational training in spatially-complex subjects and one's spatial ability, with learning in these subjects improving spatial ability over time, and higher spatial ability in turn being correlated with improved educational outcomes in these subjects. Performance in the geological sciences has been shown to be correlated with students' spatial ability, which has been found to improve over the duration of their program. Students in higher-level geology courses have been found to have significantly higher spatial ability scores than students in introductory courses (Titus and Horsman 2009). Similarly, success in anatomical education has also been positively correlated with students' spatial ability (Fernandez, Dror, and Smith 2011; Lufler et al. 2012; Nguyen, Nelson, and Wilson 2012). When comparing among students enrolled in different programs of study, anatomy students have been shown to have overall higher spatial ability as well as greater improvements in their performance over consecutive iterations of mental rotation test, as compared to students in educational sciences (Vorstenbosch et al. 2013a). Further investigation is warranted to elucidate the role of spatial ability in learning to better inform and implement educational strategies to assist students with low spatial abilities. As evidence suggest that spatial ability is moderately malleable in nature, additional training and support of spatial cognitive skill

development may be effective in increasing both spatial abilities and learning outcomes in the anatomy classroom.

## 1.4 Research Objectives

The initial aim of this research was the development an interactive 3D neuroanatomy resource that was deployable in an online format, with the capability of collecting data from participants' sessions, in order to quantify and evaluate patterns in users' interactions. Additionally, this research aimed to determine the impact of the integration of 3D e-learning resource on students' knowledge in neuroanatomy, as compared to conventional instructional resources including both cadaveric laboratory specimens and comparable online resources that utilize 2D images and illustrations. Furthermore, the research aimed to elucidate the impact that individual differences in spatial ability may have on student interactions and learning outcomes with an interactive 3D e-learning resource when completing learning spatial neuroanatomy objectives, as measured by both a conventional multiple-choice assessment and a novel digital syncretion assessment.

It is hypothesized that the utilization of an interactive, dynamic 3D e-learning resource will lead to improved spatial neuroanatomy knowledge, as measured by both spatial knowledge quiz scores and performance on virtual syncretion tasks. It is further hypothesized that a larger effect will be observed for learners with low spatial ability, as the 3D resource will be beneficial in modulating the difficulties experienced by these students in learning complex spatial relationships, thus decreasing the performance gap between high and low spatial ability learners.

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## Chapter 2

### 2 Development of an Interactive 3D E-Learning Resource for Enhanced Neuroanatomy Education

This chapter describes the motivation behind the development an interactive 3D, web-based e-learning resource, its design, and adaptations made following preliminary deployment in an undergraduate anatomy laboratory.

#### 2.1 Rationale for the Development of a 3D Interactive Neuroanatomy E-Learning Resource

The drivers for curricular change in the anatomical sciences have been encouraged by the implementation of innovative teaching pedagogies, the integration of innovative educational technologies, and the creation of novel assessment modalities, which are all increasing in popularity. Trends in curricular changes have been previously quantified, with a past study reporting a 55% decrease in the amount of course hours in gross anatomy between 1955 and 2009 (Drake et al. 2009). In contrast, a more recent survey has found a possible reversal in this trend, with classroom hours in both gross anatomy and neuroanatomy increasing by 24% and 29% respectively between 2014 and 2017 (McBride and Drake 2018). This increase was in juxtaposition to the decrease in laboratory hours in gross anatomy and neuroanatomy by 16% and 38% respectively (McBride and Drake 2018). The integration of complementary educational technologies, including synchronous and asynchronous e-learning tutorials, and 3D interactive resources in the gross anatomy, specially neuroanatomy, may provide students with the opportunities to review and develop their anatomical knowledge despite declining classroom hours, however, the impact of these changes has yet to be evaluated fully.

The study of gross anatomy has served as a fundamental component of education for students in the allied health sciences, by providing an opportunity to develop and apply a 3D understanding of the structural and functional intricacies of the human body, that is essential for future health care professionals. Students must develop a robust understanding of 3D spatial information in order to be able to effectively treat their

patients however, for novice students of the anatomical sciences, learning is a complex and challenging process of development, verification, and modifications or revisions, as they seek to master the multifaceted and interconnected nature of many structures. Once students have consolidated new anatomical knowledge from traditional resources, this information must be applied to both normal and pathological states to help understand anatomical structures and their role in both health and disease. Given the highly spatial nature of the content, past studies have found that one's level of spatial ability may be positively correlated with successful anatomy learning outcomes (Guillot et al. 2007; Langlois et al. 2009; Lufner et al. 2012) and performance on spatial anatomy tasks (Nguyen, Nelson, and Wilson 2012). Furthermore, there is evidence to indicate a potential reciprocal relationship between spatial ability and success in learning practical and spatial aspects of anatomy (Nguyen, Nelson, and Wilson 2012; Vorstenbosch et al. 2013b; Langlois et al. 2017), whereby low spatial ability learners could enhance their spatial ability by engaging in topics of high spatial complexity, which in turn may increase their success in achieving a greater understanding and achievement in anatomy. Training in the anatomical sciences provides knowledge and skills that act as a scaffold to assist students in developing 3D mental representations, which will be essential in shaping their future decisions for diagnosis and intervention in the clinical setting (Marks 2000; Aziz et al. 2002; Heath and Cohen-Gadol 2012).

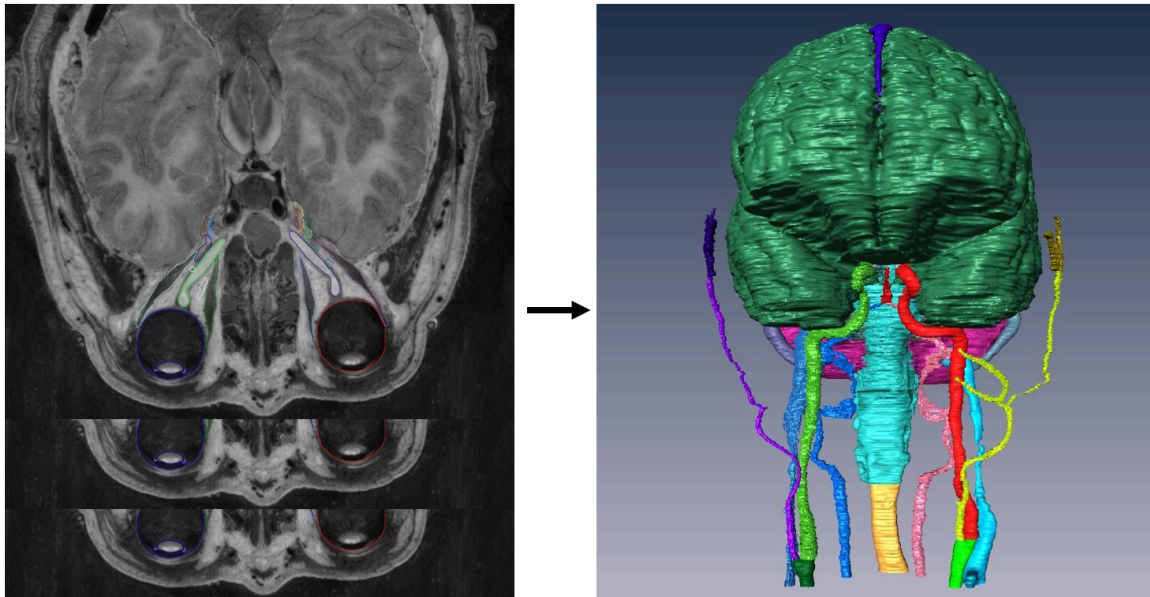
Neuroanatomy is one of the most challenging topics in anatomy, with many novice students reporting they have the least amount of knowledge in the clinical neurological sciences (Jozefowicz 1994; Lim and Seet 2008; Giles 2010;). A main contributor to the challenges reported by novice students is complexity of the spatial relationships that exists between numerous structures, and a perceived difficulty in developing a clear spatial understanding of this information. The combination of the reduction in curricular and laboratory hours devoted to neuroanatomy education, in conjunction with the limited supply of physical neuroanatomical models and specimens, has made the task of mastering neuroanatomy increasingly difficult for incoming allied health sciences students. The development and deployment of efficient and effective 3D e-learning neuroanatomy resources may help mitigate the challenges encountered by students, as 3D resources could serve as scaffolds to assist students in forming clear and accurate mental

representations of the complex spatial information essential for a better understanding of spatial neuroanatomy.

## 2.2 Methodology for Development of an Interactive 3D E-learning resource

### 2.2.1 Formation of 3D Anatomical Structures

The initial step in the creation of the 3D neuroanatomy e-learning resource involved the development of individual 3D digital structures, that could be merged to form a complete anatomical model. The creation of each digital structure was accomplished by selecting a subset of six hundred thirty-two sequential transverse cryosection images from the Visible Human Project Female dataset (Ackerman 1998) which were compiled, and converted to gray-scale images (Adobe CS3, San Jose, CA) before being imported into Amira software, version 5.6 (FEI Visualization Services Group, Hillsboro, OR). The process of manual segmentation required the examination of axial, coronal, and sagittal planes to identify and select the voxels necessary to build the 3D volumetric representations, known as meshes, for each of the desired neuroanatomy structures visible in the 2D image dataset (Nguyen and Wilson 2009; Sergovich, Johnson, and Wilson 2010; Brewer et al. 2012; Allen, Bhattacharyya, and Wilson 2015). Once the boundaries of a specific anatomical structure were identified by segmentation, the image voxels were assigned to the structure's material, a process that was repeated for each image enabling the formation of user-determined 3D volumetric representation for each of the desired structures (Figure 3). Each anatomical structure was exported as a separate *Wavefront OBJ* file from Amira into a computer graphics software to achieve digital refinement of the meshes' esthetics, and facilitate the generation of an interactive user interface.

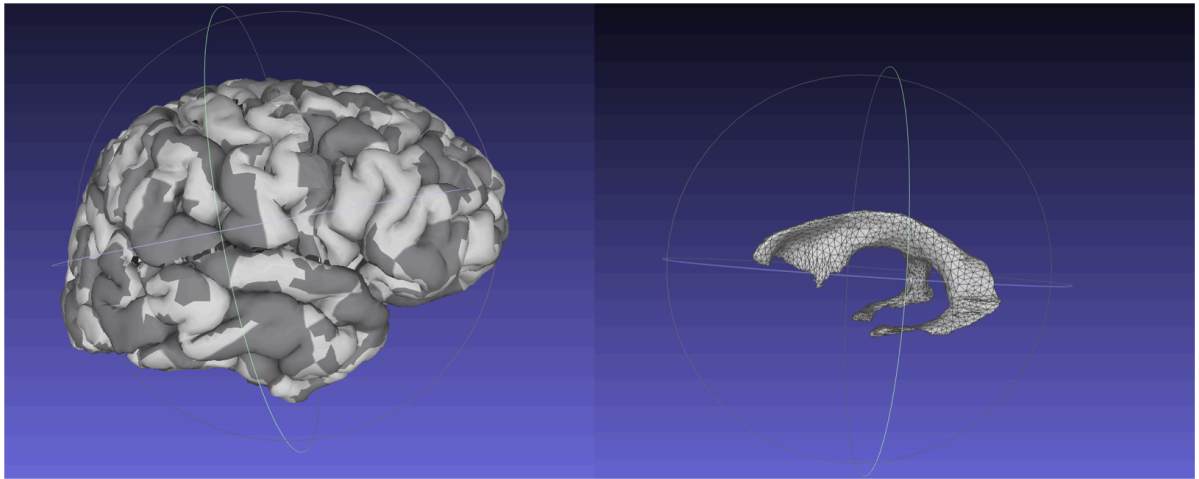


**Figure 3: Overview of the manual segmentation process that was utilized in Amira 5.6 software to build the 3D representations (meshes) for the structures included in the neuroanatomy model. Selection of the area (voxels) in each image representing a specific structure was assigned to the structure's material. The material for structure was assigned a different coloured mesh by the Amira software. The resultant 3D meshes produced by the segmentation are displayed in the right panel of the image.**



### 2.2.2 Refinements of 3D Structural Meshes

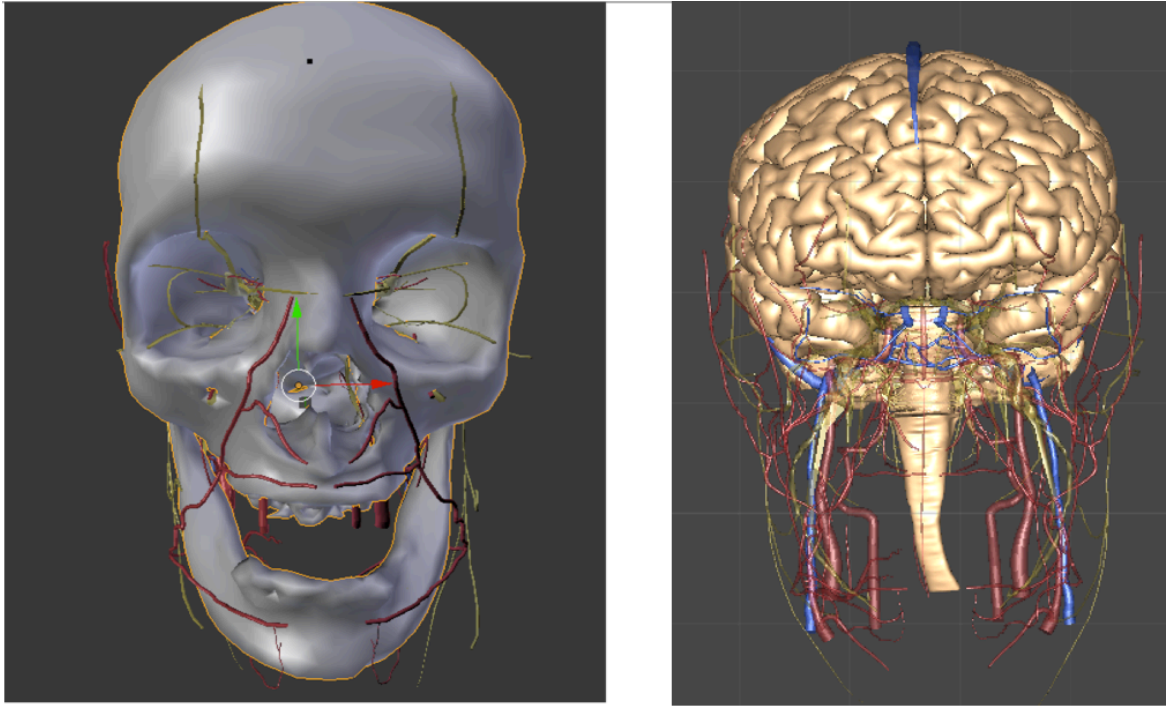
The subsequent refinement of the mesh for each anatomical structure was achieved through a multi-step process, the first of which required the use of the 3D mesh processing software MeshLab (Mesh Lab 1.2.1., ISTI-CNR, Pisa, IT). Three filters available as part of this program were sequentially applied to repair and optimize the esthetics of the 3D structural meshes without impacting the anatomical accuracy of the structures (Figure 4). The *Re-orient all faces coherently* filter was used to ensure that all components of the mesh surface, called faces, were placed in the correct direction, in order to allow the chosen textures to be applied correctly. A limitation of the meshes that were created and directly exported from Amira, was the very high number of faces that often exceeded the limit that other computer graphics and game engine software accept. In order to resolve this issue, the *Quadratic Edge Decimation* filter was applied to each structure's mesh, which systematically reduced the number of faces each mesh was composed of, while maintaining the same boundaries and topologies to preserve anatomical accuracy. The final filter that was applied to the 3D structural meshes was the *Laplacian Smoothing* function. This was necessary to improve the visual esthetics of the meshes exported from Amira, which have a distinct step-like appear on their surface. The *Laplacian Smoothing* filter flattened the mesh surfaces to provide a smoother, more realistic appearance while removing digital artefacts or surface anomalies for each of the structures (Figure 4) (Allen et al. 2016).



**Figure 4: Overview of the process completed in MeshLab 1.2.1 software to repair the minor errors created during the manual segmentation process. The filters within this program were used to reduce the digital size of each mesh and repair any surface anomalies that would prevent the inclusion of the structures in the 3D model. The image on the left illustrates the need to apply the Quadratic Edge Decimation filter to reduce the number of faces within the cortex 3D mesh, while the heterogenous shading indicates some faces are inverted and the reorienting filter is required to ensure they are all facing the correct direction. The image on the right displays the smoothed appearance of the lateral ventricle mesh after the Laplacian Smoothing filter was applied to reduce the step-like appearance produced in the initial creation of the meshes.**

### 2.2.3 Assembly of the Full 3D Neuroanatomy Model

Following completion of the digital refinements to the surface esthetics, each mesh was imported into the computer graphics software Blender 3D (Blender 3D 3.4, Blender Foundation, Amsterdam, Netherlands), an open-source program capable of assembling 3D mesh structures into a full 3D model with the opportunity for the addition of functions including animations, printing of 3D models, and the creation of files that may be utilized by game engines to create interactive user interfaces. Additionally, a limitation of the segmentation process in Amira was the inability to visualize extremely thin or small structures, including small arteries and veins, the dural sinuses and cranial nerves. When modelled in Amira, these structures did not appear continuous, but rather appeared as fragmented groups of voxels intermittently spaced along the course of the vessel or nerve. The vasculature and cranial nerve structures were modeled within Blender 3D using Clinically Oriented Anatomy 6<sup>th</sup> edition (Moore 2009), Gray's Anatomy 40<sup>th</sup> edition (Strandring 2008), and Atlas of Human Anatomy 6<sup>th</sup> edition (Netter 2014) as references. The structures were modeled individually using a basic cylinder geometry, and then progressively extended until the appropriate length of the structure was achieved. During the creation of these structures, the greatest emphasis was placed on ensuring the accuracy of the vessel or nerve with respect to related anatomical landmarks within the segmented model. The full set of vessels and nerves were modeled for the right side of the head, and then the *Mirror* function was used in the Blender 3D software to create the corresponding contralateral structures on the left side of the head. A frontal view of the completed 3D model that was incorporated into the 3D e-learning resource is presented in Figure 5 (Allen et al. 2016). A complete list of the neuroanatomical structures that were segmented and included within the reconstructed 3D model is shown in Table 1.



**Figure 5: Frontal view of the reconstructed neuroanatomy model in Blender 2.6 with the skull visible and removed respectively. The image on the right provides an anterior view of the frontal and temporal cortical lobes, as well as the external carotid and vertebral arteries and some of their primary branches, the external jugular vein and superior sagittal dural sinus.**

**Table 1: Neuroanatomy structures segmented in Amira or modelled in Blender 3D, which were included in the 3D neuroanatomy model**

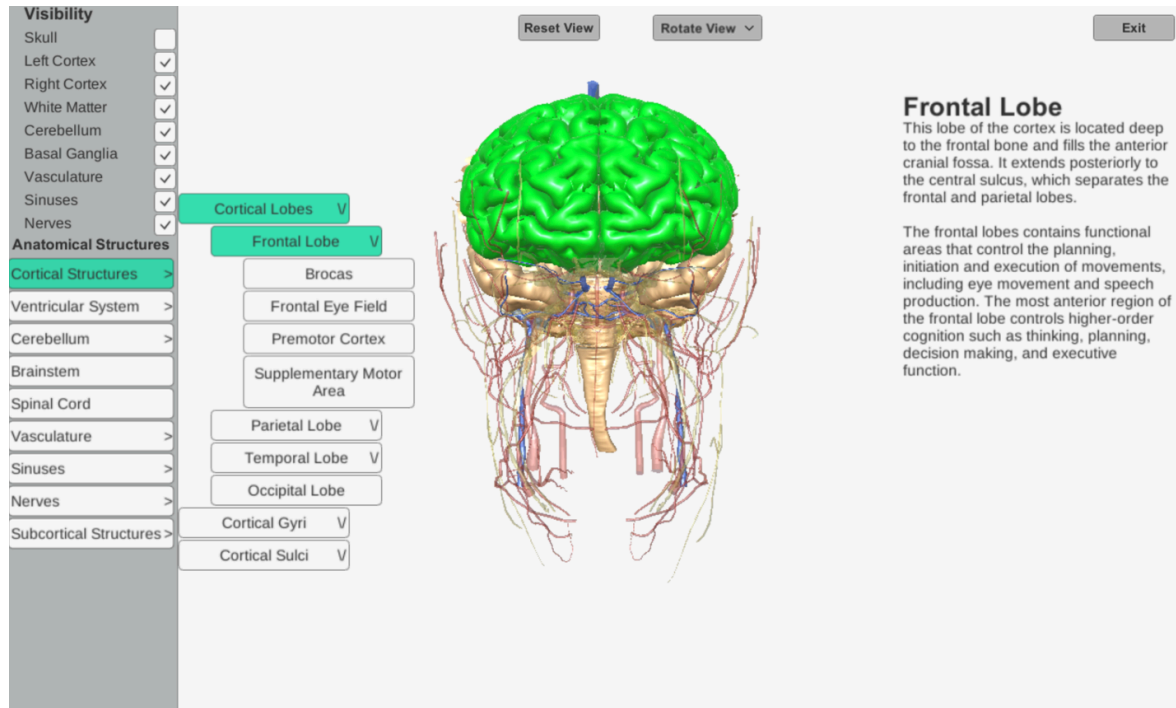
Structures Segmented in Amira			
Cortical Structures			
Cortical Lobes (Frontal, Parietal, Temporal and Occipital)	Cortical Sulci (Central, Lateral, Parieto-Occipital, Longitudinal Fissure)	Cortical Gyri (Postcentral, Precentral, Cingulate)	Cortical Functional Areas (Frontal Eye Field, Broca's, Wernicke's, Supplementary Motor Area)
Ventricular System			
Cerebral Aqueduct	Lateral Ventricles	Third Ventricle	Fourth Ventricle
Subcortical Structures			
Globus Pallidus	Thalamus	Thalamus	Putamen
Corpus Callosum	Fornix	Caudate Nucleus	White Matter
Cerebellar Structures and Brainstem			
Brainstem	Cerebellar Vermis	Cerebellar White Matter	Cerebellar Peduncles
Cerebellar Hemispheres			
Structures Modelled in Blender 3D			
Cranial Nerves (I-II)	Vertebral Arteries and main branches	Basilar Artery and main branches	Communicating Arteries (Anterior, Posterior)
External Carotid Artery (and branches)	Internal Carotid Artery and main branches	Internal Jugular Vein	

#### 2.2.4 Creation of an Interactive User Interface for the 3D Neuroanatomy Model

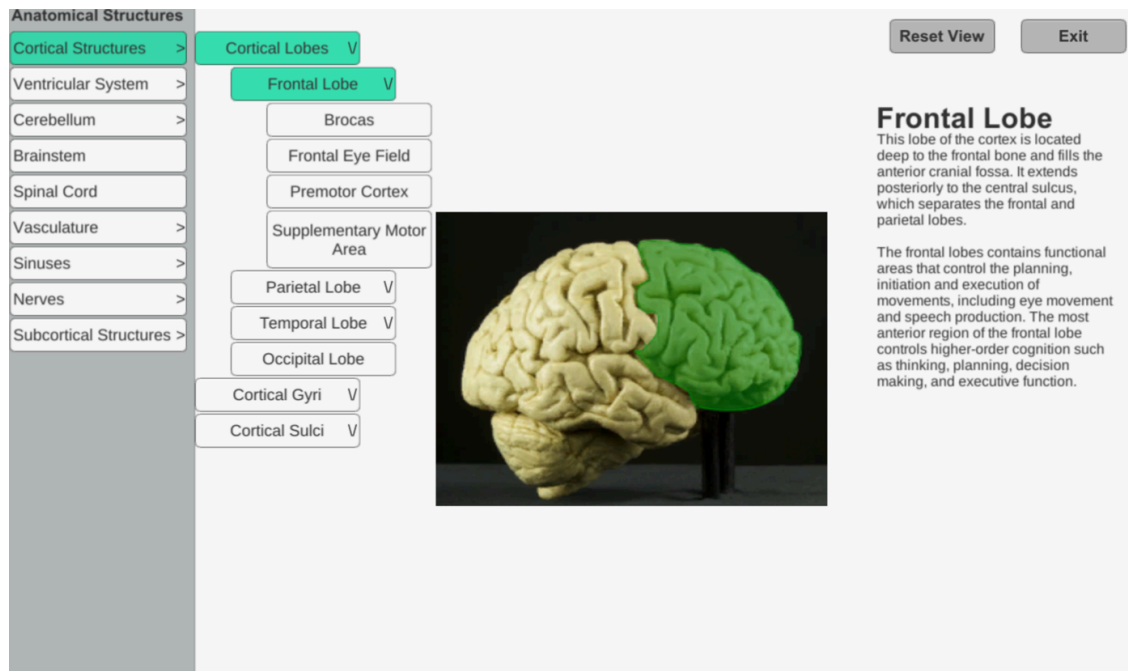
Once the 3D model was fully assembled in the Blender 3D software, the final step in the creation of the 3D neuroanatomy e-learning resource, was the development of a user interface that created an engaging and interactive digital environment that promoted a student-centered experience. Since the 3D model was delivered without stereoscopic perspective, in this learning module 3D may be defined as a 2D model that is interactive to allow for a 3D perspective through the ability to modify the rotation and location of the model within the virtual world. The module's user interface was designed using C# coding language to provide a self-paced learning environment in which the students were capable of controlling both the content they viewed, as well as the pace by which they received the information. Previous studies have found that the success of learning experiences is dependent upon the learner's cognitive activity level, rather than physical activity level during learning (Mayer 2005). As a result, features including an interactive menu, control of viewpoint and level of magnification of the model, and the ability to control the visibility of structures were incorporated to encourage learners to take an active role in their learning while using the interface. Conversely, the 2D e-learning resource was designed to allow for the inclusion of either the 3D model (Figure 6) created in blender or two-dimensional (2D) images of the neuroanatomy content presented (Figure 7). The 2D images were accessed from the "Self-Directed Neuroanatomy Laboratory" created by the Department of Anatomy and Cell Biology at Western University. Since the location and rotation of images presented within the 2D e-learning resource could not be manipulated by the user, is created only a 2D perspective of the structures presented.

The Unity 5.4 software enabled the development of the user interface in formats compatible with Mac, Windows, Android, and WebGL platforms. The WebGL platform was chosen for the creation of the user interface, as it allowed for the deployment of the learning resource on a secure web server, which allowed for the collection of user data including user name, mouse and key interactions with models, and duration of time spent accessing the model. The flexibility of the user interface to incorporate different image

modalities with identical functions and menu, while also collecting user interaction data was essential to allow for future evaluation of the 3D learning resource in comparison with conventional learning resources.



**Figure 6: View of the 3D learning module user interface created using Unity 5.4 software. The selection of the frontal lobe has been demonstrated in the interactive menu on the left side of the screen, causing the appearance of related text on the right side of the screen and the colour highlighting of the frontal lobe within the 3D model bilaterally.**



**Figure 7: View of the equivalent 2D learning module user interface created using Unity 5.4 software. The selection of the frontal lobe has been demonstrated in the interactive menu on the left side of the screen, causing the appearance of related text on the right side of the screen and the colour highlighting of the frontal lobe within the chosen image. The 2D images were accessed from the “Self-Directed Neuroanatomy Laboratory” created by the Department of Anatomy and Cell Biology at Western University (<http://360anatomy.uwo.ca>).**



### 2.2.5 Cognitive Load Theory Considerations for Module Interface Development

Effective instructional design is driven by our increasing knowledge of the organization and relationships between cognitive structures and processes. A prominent theory that has been important in designing effective learning materials, and is guided by our knowledge of human cognitive architecture, is Cognitive Load Theory (CLT). The principles of the CLT may be applied to many different learning modalities, including multimedia learning, which is defined as spoken or written words in coordination with illustrations that may be in the form of pictures, diagrams or animations (Sweller 2005). Several assumptions of the CLT were integrated during the development process of the user interface for the 3D neuroanatomy module, with the intent of enhancing student learning outcomes through the mitigation of extraneous cognitive load. Extraneous cognitive load is the burden imposed on an individual's working memory as a result of the design and format of instructional methods (Sweller 2005). By following several principles outlined by the CLT thought to reduce the amount of extraneous load experienced by the students, the design of the learning module was intended to facilitate improved learning of the neuroanatomy information.

The multimedia principle, which postulates that learning is improved when people are presented with both word and pictures as compared to words alone, was adhered to by simultaneously presenting 3D visual information from within the model, in conjunction with related text describing structural and functional details of a selected structure. Additionally, the limited capacity assumption of CLT suggested the amount of information that may be processed during a learning experience by working memory is limited in size, with a maximum of approximately five to seven items at any one time. As a consequence of the limited amount of information that may be processed by a learner, it has been demonstrated that individuals' learning can be enhanced by the removal of extraneous information, which has been termed the coherence effect (Mayer and Moreno 2003). Consequently, in order to present only essential information to learners in controlled amounts, the information was divided into smaller "chunks" that could be accessed individually through an interactive menu, and all visual and textual information

was evaluated prior to being incorporated in the learning module. Components that were determined to be supplementary or nonessential to the completion of the learning objectives outlined were excluded from the module. Furthermore, the signaling principle demonstrates that focusing learners' attention on the essential information during a task has a positive effect on knowledge acquisition and transfer by reducing the effort the individual has to invest to visually search an image. In order to adhere to the suggestions of this principle, the design of the learning module also included a highlighting function, which changed the colour of a selected structure to a bright green hue. This feature was intended to direct the learner's attention to the specific structure, while minimizing the time and effort required for them to locate it within the model. Lastly, the interactive module included labels for anatomical structures that were only visible when users placed their mouse near a particular structure. When visible, the label related to each structure was located adjacent to the arrow image of the mouse, a feature was consistent with the spatial contiguity principle that describes people are better able to learn from a multimedia resource when corresponding words and images are presented in close proximity to each other rather than further apart on the screen.

## 2.3 Preliminary Outcomes

The preliminary evaluation of the 3D e-learning resource was approved by the Research Ethics Board at the University of Western Ontario (REB# 104870) (Appendix A) and was conducted in the Neuroanatomy, Eye and Ear laboratory section of the second year of the undergraduate medicine program. A total of 174 students were eligible to participate, with a total of 47 students, 22 males and 25 females, successfully completing all components of the study. The average age of the participants was 23.8 years of age. The study followed a pseudo-randomized crossover design which randomly assigned student laboratory dissection groups to one of two experimental groups which viewed the different learning modalities in reverse order. During the experimental intervention, Group A was initially provided access to the 3D e-learning resource, followed by exposure to the cadaveric laboratory resources. Conversely, participants in Group B were given initial access to the cadaveric laboratory resources, followed by exposure to the 3D e-learning resource. All students completed three assessments of spatial and functional

anatomy knowledge including a baseline quiz prior to receiving any laboratory instruction, quiz #1 following exposure to the first learning resource, and quiz #2 after viewing the second and final learning modality during the laboratory instruction period. All components of the evaluation of the 3D e-learning resource were completed during the 3-hour laboratory instruction period allotted in the current curriculum.

In the current study, the anatomy knowledge assessments each consisted of fifteen questions developed by the authors and approved by faculty member of the Schulich School and Medicine and Dentistry, to ensure they were congruent with the stated learning objectives. The questions focused on measuring participants' spatial and function understanding of neuroanatomy structures, and were separated into three distinct categories; Identification of a structure or its function when visible in the image provided, identification of a structure or its function when not visible in the image, or structural identification based on question text alone. All participants completed identical knowledge assessments at baseline, quiz #1 and quiz #2, however the set of questions presented in the baseline quiz were different than those in either quiz #1 or quiz #2. Each assessment contained equivalent proportions of each question type to avoid bias towards either learning modality. Representative exemplars of each question type contained in the assessments are presented in Appendix B.

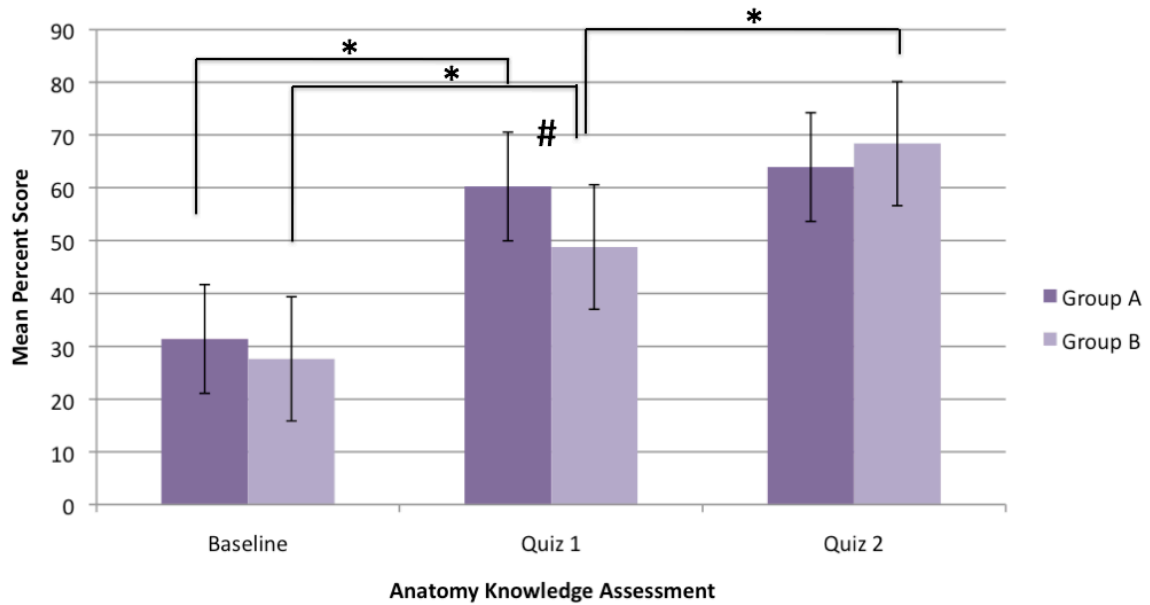
Calculations of Kendall's Tau-b values were calculated to ensure equivalent level of difficulty across assessments, with these values revealing strong associations between mean percent scores across assessments and acceptable level of validity across assessments. This calculation was required to ensure that earning a specific score on any of the spatial anatomy knowledge assessments was equal in terms of its level of difficulty, and that all assessments measured students' spatial knowledge to the same extent.

Statistical analysis was performed using R statistical software, version 3.2.2 (R Core Team, Vienna, Austria). The normality of the data was also assessed using the Shapiro-Wilk test for normality, which revealed a significant departure in the data from normality,

As the data significantly deviated from normality, further analysis of the data utilized non-parametric measures.

To examine potential difference within participant groups, Wilcoxon Signed Rank tests with a continuity correction were performed. This intragroup analysis of assessment scores (Figure 8) found participants in both groups A and B significantly improved their performance scores for the anatomy knowledge between the baselines and quiz #1 assessments ( $W=47$ ,  $P<0.01$ ;  $W=30$ ,  $P<0.01$  respectively). While participants in group A did not significantly improve their performance scores between quiz #1 and quiz #2, performance scores were significantly higher between quiz #1 and quiz #2 for participants in group B who accessed the 3D e-learning resource after exposure to the cadaveric laboratory resource ( $W=94$ ;  $P<0.01$ ).

Mann-Whitney U tests were calculated on mean percent assessment scores between participant groups within the same assessment. No significant differences were observed between groups on the baseline anatomy knowledge assessment or the Santa Barbara Solids Test for spatial ability. However, when comparisons were performed between groups on the Quiz #1 anatomy assessment, it was revealed that students in Group A, who initially accessed the 3D module performed significantly better on the anatomy knowledge assessment than students who were initially given access to the cadaveric gross anatomy resources ( $W = 397.5$ ,  $p < 0.01$ ). There were no significant differences found between groups in the final anatomy knowledge assessment after students had accessed both learning modalities. A summary of the descriptive statistics are shown in Table 2.

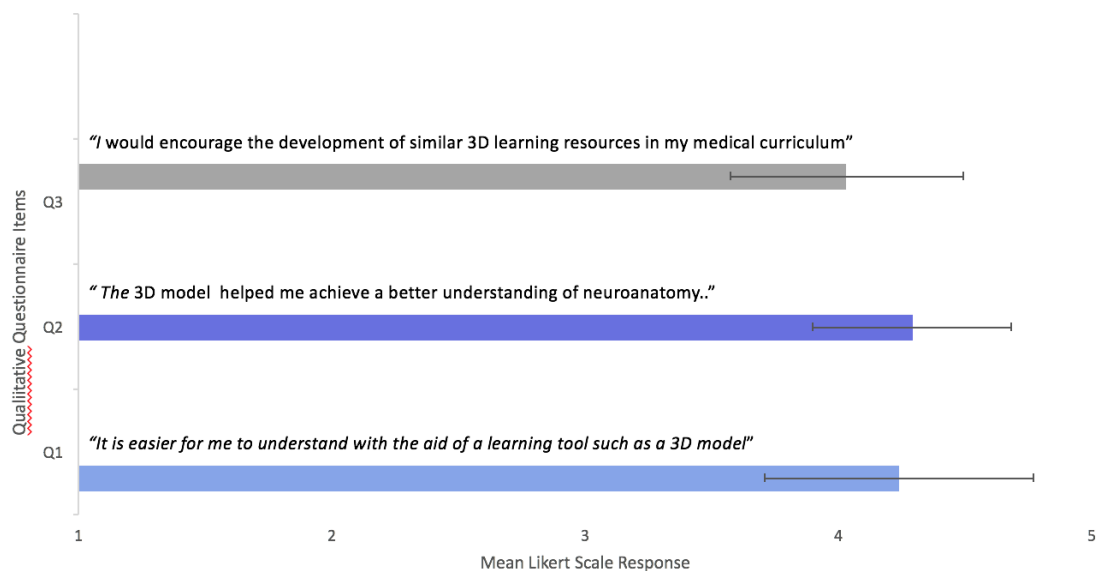


**Figure 8: Mean percent scores across anatomy knowledge assessments after exposure to each of the learning modalities (cadaveric laboratory and 3D e-learning resources). Experimental group A was exposed to the 3D e-learning resources followed by the cadaveric laboratory resources, while experimental groups B was initially exposed to the cadaveric laboratory resources followed by the 3D e-learning module. Groups A and B significantly improved their performance scores for the anatomy knowledge between the baselines and quiz #1 assessments (W=47, P<0.01; W=30, P<0.01 respectively. Only participants in group B, who accessed the 3D e-learning resource after exposure to the cadaveric laboratory resource significantly improved their scores on quiz #2 (W=94; P<0.01). \* indicates a significant difference between assessments within an experimental group, # indicates a significant difference between groups on the same assessment p<0.01.**

**Table 2: Descriptive statistics across spatial anatomy knowledge assessments subsequent to access to e-learning resource modalities for undergraduate medicine participants.**

	Mean (% $\pm$ SEM)	Median (%)	Q1 (%)	Q3(%)
Baseline Spatial Anatomy Knowledge Assessment				
Group A (2D $\rightarrow$ 3D)	31.39 $\pm$ 2.72	28.13	21.88	34.38
Group B (3D $\rightarrow$ 2D)	27.63 $\pm$ 1.56	28.13	25.00	31.25
Spatial Anatomy Post-Knowledge Assessment #1				
Group A (2D $\rightarrow$ 3D)	60.23 $\pm$ 2.52	55.56	51.39	70.83
Group B (3D $\rightarrow$ 2D)	48.78 $\pm$ 2.59	47.22	38.89	61.11
Spatial Anatomy Post-Knowledge Assessment #2				
Group A (2D $\rightarrow$ 3D)	63.90 $\pm$ 3.56	64.71	56.62	75.00
Group B (3D $\rightarrow$ 2D)	68.35 $\pm$ 2.76	70.59	58.82	76.47

Qualitative analysis of the students' perceived learning experiences with the learning modalities was also completed using a 5-point Likert scale format questionnaire (Figure 9): 1= strongly disagree, 5=strongly agree. The questionnaire was completed after participants accessed both learning resources, and collected subjective evaluations and perceptions towards both learning modalities and their impact on learning spatial neuroanatomy. Most participants perceived the incorporation of the 3D e-learning resource as a positive addition to their learning experience, with a high level of agreement with statements such as "It is easier for me to understand anatomy concepts when I can visualize them with the aid of a learning tool such as a 3D model" (Mean =  $4.24 \pm 0.46$ , range 1-5), and "The incorporation of the 3D enables me to form a better understanding of the neuroanatomy compared to traditional resources" (Mean =  $4.29 \pm 0.40$ , range 1-5)



**Figure 9: Participant responses questions from a subset of questions from the 5-point Likert scale questionnaire measure subjective attitudes and opinions of the learning modalities utilized during the neuroanatomy laboratory instruction (1=strongly disagree – 5 = strongly agree). Participants' feedback on the 3D e-learning resource was largely positive, with mean responses of  $4.24 \pm 0.46$ ,  $4.29 \pm 0.40$ , and  $4.04 \pm 0.53$  on questions 1-3 respectively.**

## 2.4 Discussion

### 2.4.1 Implementation of Changes during Deployment and Evaluation of 3D E-Learning Module

The 3D e-learning resource was successfully integrated into the neuroanatomy laboratory curriculum for second year undergraduate medical students, with participants completing both quantitative and qualitative assessments to guide future modifications and improvements to the delivery of the e-learning resource and content of the anatomy assessments. Preliminary quantitative evaluation of the 3D e-learning module in the neuroanatomy laboratory curriculum demonstrated its integration significantly improved student performance on knowledge assessments of spatial and functional neuroanatomy. Additionally, participants displayed positive attitudes towards the development and integration of similar 3D learning resources to supplement their anatomy instruction. Participants perceived the 3D e-learning resource facilitated their ability to visualize and learn spatial neuroanatomy. These results support findings from past studies in our lab that reported the positive effect of 3D e-learning resources on training for neurosurgical procedures (Brewer et al., 2012), and the acquisition of anatomical knowledge in neuroanatomy (Chariker, Pani, and Naaz 2011; Ruisoto Palomera, Juanes Méndez, and Prats Galino 2014a) as well other areas of anatomy including ophthalmology (Glittenberg and Binder 2006) and osteology (Venail et al. 2010b). In particular, a recent finding has shown that a 3D learning resource may facilitate the learning of c-shaped neuroanatomy structure, which are located subcortically, and have a greater level of spatial complexity as compared to cortical lobes (Drapkin et al. 2015).

It was determined that the number of questions contained within each assessment did not provide an adequate sample size to conduct separate analyses for items measuring knowledge across different question types. Following the preliminary evaluation of the 3D e-learning resource, the number of questions within each assessment was increased to twenty-five items in order to allow for such analyses in future studies to determine if the effect of the learning modality used may differentially impact the learning outcomes on each type of question presented.



## 2.4.2 Future Trends for Teaching and Learning in Anatomy

There is increasing interest and demand for creative and innovative learning and assessment resources in medical education, and more specifically in anatomical education. Due to its high level of spatial complexity and below average level of student comprehension when using conventional learning resources (Ridsdale, Massey, and Clark 2007; Zinchuk et al. 2010), neuroanatomy is a sub-topic in anatomy education in which student learning may benefit most from the integration of novel 3D learning materials. With continuing reform to many aspects of anatomy curricula, including amount of in-class and laboratory hours (Drake et al. 2009; Drake, McBride, and Pawlina 2014; McBride and Drake 2018), as well as the teaching and learning resources that are being developed and utilized, it is essential that effective and efficient pedagogies and resources are implemented into neuroanatomy to support students' learning. The preliminary findings of this study provide evidence that contrasts with some past studies that have found the integration of 3D e-learning resources to have neutral or negative impacts on learning outcomes (Garg et al. 1999a; Garg et al. 2002; Keedy et al. 2011; Preece et al. 2013). Several factors including the higher degree of spatial complexity of the anatomical structures studied, in addition to the close adherence to several principles of Cognitive Load Theory for multimedia learning, and the fully interactive nature of the 3D e-learning module, which may have facilitated active learning while using the resource, could provide an explanation for the differences observed. Previous studies have found that by engaging in active learning, students were able to achieve higher levels of knowledge acquisition and retention, as compared to students who undertook more superficial or passive learning approaches (Rhem 1995; McManus et al. 1998). Furthermore, an assessment of learning styles among allied health sciences students reveal the 58% students within this group had multiple learning preferences with the Visual Auditory Reading and Kinesthetic learning styles inventory, and were classified as multimodal learners (Breckler, Joun, and Ngo 2009). The percent of multimodal learners was even greater among students in the medical sciences specifically, with 69% of premedical students and 64% of medical students identified as having multimodal learning preferences. Such findings suggest that multimodal curricula may better suit the learning preferences and strength of this group of students.

## 2.5 Conclusions

An online 3D learning resource was developed and implemented into an existing neuroanatomy laboratory course in the second year of the undergraduate medicine program. The evaluation of this resource found there was a significant improvement in students' performance anatomy knowledge test scores following interaction and manipulations of the novel 3D resource as compared to the use of conventional 2D learning resources. For students in the clinical neurological sciences, successful performance in their future clinical professions is dependent upon acquiring spatial anatomy knowledge and several multimodal skills that are essential for interpreting clinical images, analyzing spatial relationships, and performing clinical procedures. Thus, in addition to improving their learning outcomes, effective development of novel learning resources guided by learning theories, may provide students with the opportunity to raise their awareness of the most effective methods they should use to master these essential professional skills.

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## Chapter 3

### 3 Evaluation of the Impact of the 3D E-Learning Resource on Neuroanatomy Learning Outcomes

This chapter describes the evaluation of the previously developed interactive 3D, web-based e-learning resource following its integration into both an undergraduate medicine neuroanatomy laboratory, and a third-year undergraduate systemic human anatomy course during the neuroanatomy block of instruction.

#### 3.1 Integration of E-Learning in Anatomy Curricula

Learning anatomy requires the identification and comprehension of complex structures in 3D space (Berney et al. 2015; Peterson and Mlynarczyk 2016). Traditionally, anatomy education is centered around cadaveric dissection, however there are substantial financial, ethical, and logistical constraints associated with the use of cadaveric specimens (Moro et al. 2017). Cadaveric learning materials are often supplemented by 2D images to assist students with their construction of 3D mental representations, which must be transformable and adaptable in order for students to be successful in anatomy, especially in spatially-complex disciplines (Cui et al. 2017). However, an issue with students' mental representations is their susceptibility to contain errors, as they are completed on the basis of students' assumptions, and may incorporate inaccuracies and misunderstandings if there are deficits in students' anatomical knowledge (Liesefeld, Fu, and Zimmer 2015). As pressures increase to effectively teach anatomy despite the reduction of hours for gross anatomy, and specifically neuroanatomy (Drake et al. 2009; Drake, McBride, and Pawlina 2014), e-learning may address this need by developing more efficient and flexible tools to support student learning (Vernon and Peckham 2002; Tam et al. 2009; Alpern, Belitsky, and Long 2011). As teaching methods modernize, with greater reliance on technologies such as 3D models, imaging and virtual reality simulations, there is evidence to suggest the best way to teach anatomy is not with one modality, but rather an integration of a combination of multiple resources (Sugand, Abrahams, and Khurana 2010; Lewis et al. 2014; Moro et al. 2017;). A review of anatomy teaching practices suggests that the course design which best promotes learning



integrates dissection or prosection with interactive multimedia, procedural anatomy, surface anatomy and imaging resources.(Sugand, Abrahams, and Khurana 2010)

Generally, 3D educational technologies can often be categorized into two formats, as either virtual simulations, that mimic real world situations, or computer-generated visualizations (Lee and Wong 2008). In anatomy education specifically, e-learning resources most frequently involve methods for displaying 3D images of complex anatomical structures (Luursema et al. 2006; McLachlan et al. 2004; Nguyen and Wilson 2009; Chariker, Pani, and Naaz 2011; De Ribaupierre and Wilson 2012; Ruisoto Palomera, Juanes Méndez, and Prats Galino 2014b; Cui et al. 2017;). Such 3D visualizations have been shown to be especially beneficial for learning anatomical regions with high complexity where traditional methods of dissection are often limited in their effectiveness (Preece et al. 2013). This view has been supported by the positive evaluations of 3D resources utilized for spatially-complex anatomical regions including the vestibular system (Nicholson et al. 2006), oculomotor system (Glittenberg and Binder 2006), vascular system (Peterson and Mlynarczyk 2016; Cui et al. 2017), and neural pathways (Yeung, Fung, and Wilson 2011;Küçük, Kapakin, and Göktaş 2016). Qualitative evaluations of 3D anatomical models have found students frequently display higher levels of interest and satisfaction when using 3D resources to learn anatomical structures (Battulga et al. 2012), and also exhibited higher levels of engagement with 3D models as measured by greater lengths of time spent exploring 3D models as compared to conventional learning materials.

In neuroanatomy specifically, students require an excellent knowledge of anatomy in conjunction with a strong ability to navigate and transform 3D space to understand the spatial relationships between structures. Spatial relationships in brain anatomy are particularly difficult to teach with conventional pedagogical methods due to limitations imposed by small, confined spaces for dissection to occur, as well as difficulties experienced by students to effectively visualize structures (Javaid et al. 2018), which may be attributed in part to the complexity and homogenous appearance of multiple subcortical structures. The use of 3D models to teach neuroanatomy has been introduced in some institutions (Estevez, Lindgren, and Bergethon 2010; Chariker, Pani, and Naaz

2011; De Ribaupierre and Wilson 2012; Drapkin et al. 2015), however further evaluation is required to gain a greater understanding of the most effective implementation of such resources to elucidate the optimal design and deployment of 3D e-learning tools, in order to best support student learning of the complexities of neuroanatomy.

## 3.2 Methodology

### 3.2.1 Study Population

The initial part of this study was conducted in the laboratory section of the Neuroanatomy, Eye and Ear course in the second year of the integrated curriculum of the undergraduate medicine program. A total of one hundred seventy-four students were enrolled in their second year of the program and were eligible to participate in the study. A total of eighty-seven students, thirty-seven males and fifty females, successfully completed all components of the study. The average age of participants was 23.2 years. Participants were randomly assigned to one of two experimental groups, which both accessed the learning resources, however, the order in which they accessed these resources was reversed. During the experimental period, participants assigned to Group A were initially provided access to the cadaveric dissection and prosection resources, followed by access to the 3D e-learning resource. Conversely, participants in Group B were given access to the 3D e-learning resource initially, with subsequent access to the cadaveric laboratory specimens.

Additionally, a second evaluation of the 3D e-learning resource involved recruitment from a different population of undergraduate allied health sciences students, specifically from the third-year undergraduate systemic human anatomy course. A total of two hundred ninety-three students were enrolled in the course and were eligible to participate in the study, with a total of one hundred forty-four completing all components of the study. Similar to the first part of the study, participants were randomly assigned to one of two experimental groups, which also accessed the two available learning resources in reverse order. In contrast to the undergraduate medicine program, the undergraduate systemic human anatomy course did not include a dissection component. As a result, the effectiveness of the 3D e-learning resource was measured in comparison to a 2D e-

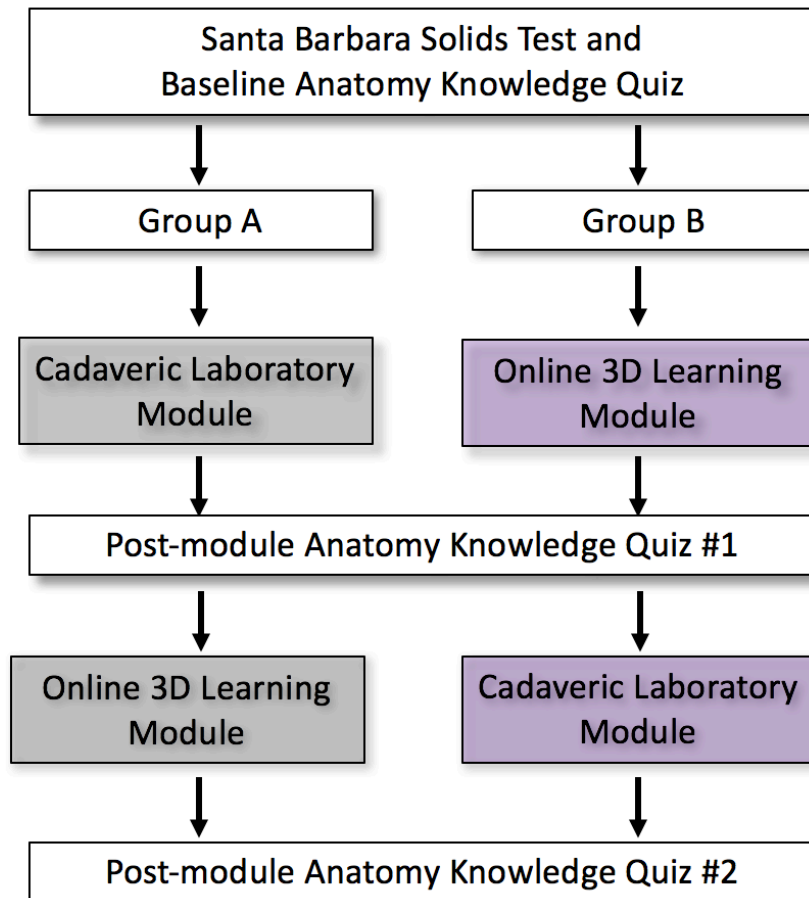
learning resource containing equivalent information consisting of descriptive text and 2D images. All components of this study were approved by the Research Ethics Board at Western University #104870 (Appendix A) and all participants provided informed consent prior to their involvement in the study.

### **3.2.2 Study Design for Integration in Neuroanatomy Medicine Laboratory**

The evaluation of the efficacy of the 3D e-learning module as an integrated resource into an undergraduate medicine laboratory course utilized a cross-over experimental design which alternated the order of exposure to learning modalities between groups as shown in Figure 10. The initial component of the study required novice participants, with no experience of neuroanatomy instruction, to complete a twenty-five question spatial anatomy knowledge baseline quiz, as well as an online version of the Santa Barbara Solids Test, a measure of the spatial ability, more specifically spatial perception skills (Cohen and Hegarty 2007, 2012). Following completion of the baseline spatial ability and neuroanatomy knowledge assessments, the participants were randomly assigned based on their assigned participant number to one of two experimental groups, and provided with access to the first learning modality, either the cadaveric laboratory specimens and dissection guidelines or the 3D e-learning resource developed and described in Chapter 2. Both groups received identical learning objectives in terms of the identification of neuroanatomical structures, their functions, and spatial relationships with other structures. Both groups were given equivalent information in terms of the amount of information included, and the level of detail presented. All participants were allowed a ninety-minute time period to engage with the learning materials, however, they were able to end their interactions once they had perceived they had successfully completed all of the required learning objectives.

Following exposure to the initial learning modality (cadaveric or 3D e-learning), all participants completed a second twenty-five question assessment of their spatial neuroanatomy knowledge to evaluate the initial impact of each learning modality on student learning. After completion of the second assessment (Post-module Anatomy Knowledge Quiz #1), participants were provided with subsequent access to the second

learning resource. Similar to the procedure with the first learning resource, students were provided with a second ninety-minute period to master the learning objectives, and were able to end their interactions with the learning resource at their own discretion when they believed they had successfully learned the information. A final twenty- five question spatial neuroanatomy knowledge assessment (Post-module Anatomy Knowledge Quiz #2) was administered following participants' exposure to the second learning modality to assess its impact on student learning. A schematic diagram of the methodology followed for evaluation of the 3D e-learning resource when integrated in to the undergraduate medicine laboratory curriculum is shown in Figure 10.



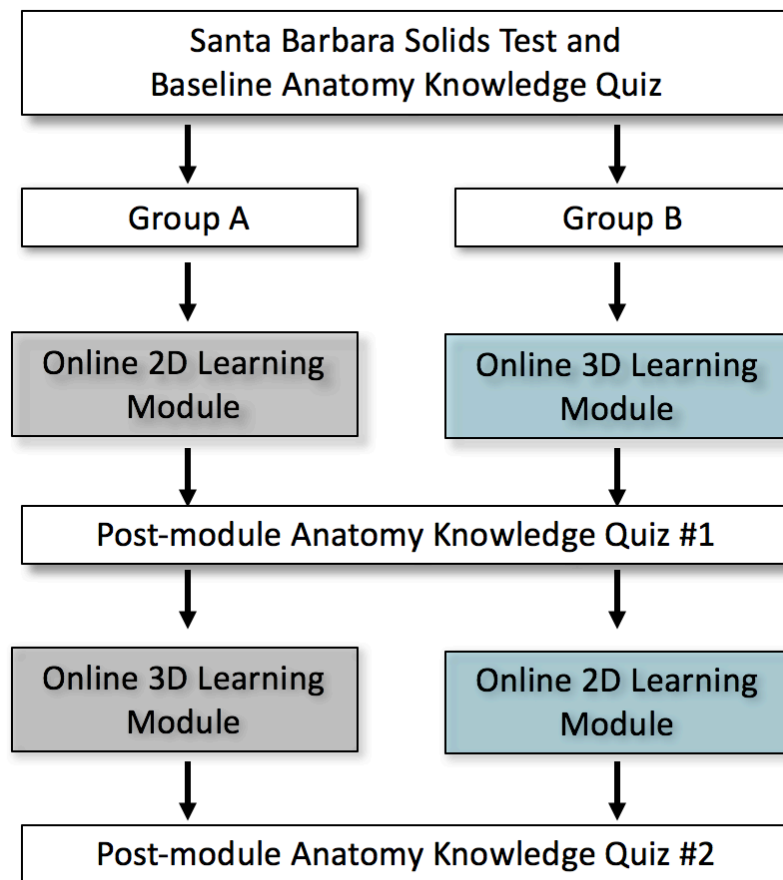
**Figure 10: Schematic diagram of the pseudorandomized cross-over study design utilized with the undergraduate medicine student population. Participants were**

**assigned to Group A or B based on the random assignment of student laboratory groups by course instructors at the beginning of the academic year.**

### **3.2.3 Study Design for Integration in Undergraduate Systemic Human Anatomy Course**

The second portion of the 3D e-learning resource evaluation sought to determine the impact of the addition of the e-learning resource of spatial neuroanatomy knowledge of undergraduate students enrolled in a senior systemic human anatomy course without a cadaveric dissection laboratory component. A total of one hundred forty-four students, ninety females and fifty-four males, successfully completed all components of the study. The average age of participants was 19.9 years. All participants completed identical baseline assessments of spatial neuroanatomy knowledge, as well as the Santa Barbara Solids Test as a measure of spatial ability. Participants were randomly assigned to one of two experimental groups, Group A or Group B, prior to accessing the first two e-learning resources. Participants appointed to Group A were given initial access to the e-learning module developed in Chapter 2, which was composed of 2D cadaveric images, anatomical diagrams, and descriptive text, whereas participants allocated to Group B were provided with initial access to the 3D e-learning module developed in Chapter 2, which was composed of the 3D neuroanatomy model and descriptive text. Following exposure to the initial learning modality (2D or 3D e-learning), all participants completed a second twenty-five question assessment of their spatial neuroanatomy knowledge (Post-module Anatomy Knowledge Quiz #1) to evaluate the initial impact of each learning modality on student learning. After completion of the second assessment, participants were provided with subsequent access to the second e-learning resource. Similar to the procedure with the first learning resource, students were asked to utilize the resource to master the learning objectives, and were able to end their interactions with the learning resource at their own discretion when they believed they had sufficiently learned the information. A final twenty-five question spatial neuroanatomy knowledge assessment (Post-module Anatomy Knowledge Quiz #2) was administered following participants exposure to the second learning modality to assess its impact on student learning.

All components of the integration of the 3D resource into the undergraduate systemic anatomy course were completed online, with all user interaction data recorded for each session. Data collected during both the 3D and 2D e-learning resources included the frequency with which structures were selected from the interactive menu, movement of the mouse within the virtual space of the resources, and length of time spent accessing each of the online resources. Data for the manipulation of the position and rotation of the model was also collected exclusively for participants' interactions the 3D e-learning resource. A schematic diagram of the methodology followed for evaluation of the 3D e-learning resource when integrated in to the undergraduate systemic human anatomy course curriculum is shown in Figure 11.



**Figure 11: Schematic diagram of the pseudorandomized cross-over study design utilized with the undergraduate third-year level systemic human anatomy course. Participants were assigned to Group A or B based on the random assignment of student laboratory groups by course instructors at the beginning of the academic year.**

### 3.2.4 Spatial Neuroanatomy Knowledge Assessment Development

Questions included within the spatial neuroanatomy knowledge assessments received approval from faculty members in the department of Anatomy and Cell Biology at Western University to confirm they satisfied the learning objectives for the neuroanatomy curricula for each course. The questions were designed to primarily assess spatial knowledge of neuroanatomy structures' locations and relationships between those structures. Questions could be categorized as identification of a structure visible in the image, identification of a structure that was not visible but had its position indicated by a distinct marker, or identification of a structure based on text alone, with no associated image provided. Images utilized in the assessments were in equal proportion of virtual models and cadaveric specimens, in order to avoid a bias based introduced by the content of the images. Additionally, the virtual and cadaveric resources captured in the assessment images differed from the learning resources provided to the participants, in order to further avoid a potential response bias due to the nature of the images. All participants completed identical assessments at each time point during the experimental period (baseline, quiz #1, and quiz #2) regardless of which learning resource they had accessed. The subsets of questions included in each of the three assessments (baseline as compared to quiz #1 or quiz #2) were not identical, however, all three assessments contained equal numbers from each category and had a maximum possible total score of thirty-three points. A representative sample of questions from each category may be referred to in Appendix B.

Calculations of Kendall's Tau-b values were performed for each of the assessments, and were found to be  $\text{Tau-b} = 0.337$ ,  $p = 0.02$ , and  $\text{Tau-b} = 0.207$ ,  $p = 0.049$  between baseline and quiz #1 and quiz #2 and quiz #1 respectively. These results demonstrated acceptable validity level between assessment as they reveal significant correlations between participants' mean percent scores across assessments.



### 3.3 Results

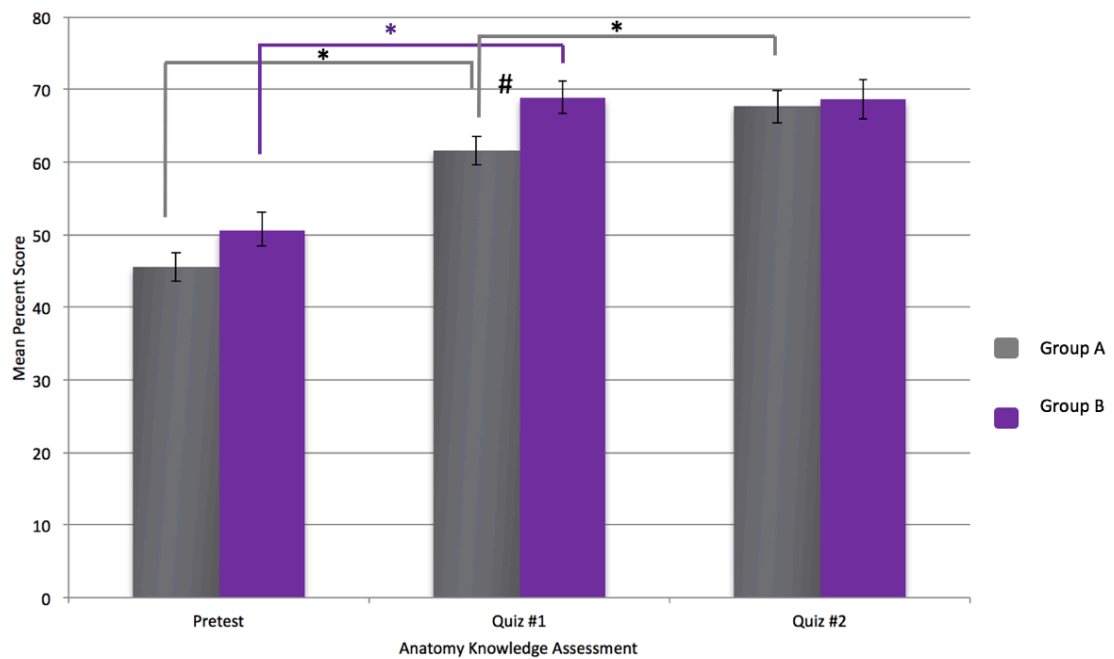
#### 3.3.1 Evaluation of 3D E-Learning Resource within the Undergraduate Medicine Laboratory

Study data were analyzed using R statistical software, version 3.2.2. (R Core Team 2013). Analysis began with the calculation of descriptive statistics for the mean percent scores for each of the baseline, quiz #1 and quiz #2 assessments. The normality of the data was also assessed using the Shapiro-Wilk test for normality, which revealed a significant departure in the data from normality,  $W=0.9791$ ,  $p=0.029$ . As the data significantly deviated from normality, further analysis of the data utilized non-parametric measures. A summary of the descriptive statistics are shown in Table 3.

To examine potential difference within participant groups, Wilcoxon Signed Rank tests with a continuity correction were performed. Participants in both Group A and Group B significantly improved their performance between the baseline and quiz #1 knowledge assessments respectively ( $W=150.5$ ,  $p<0.01$ ;  $W=13$ ,  $p<0.01$ ). Additionally, participants in Group A who accessed the 3D e-learning resource following exposure to the cadaveric laboratory resource, significantly improved their mean percent performance on quiz #2 ( $W=424$ ,  $p<0.01$ ), however, a significant result was not observed for participants in Group B who accessed the cadaveric laboratory resources following exposure to the 3D e-learning resource.

Mann-Whitney U tests were calculated on mean percent assessment scores between participant groups within the same assessment. No significant differences were observed between groups on the baseline knowledge assessment or spatial ability, as measured by the Santa Barbara Solids Test scores. Analysis between groups did reveal a significant difference between mean percent scores on quiz #1. Participants who initially accessed the 3D e-learning resource performed better than participants who were provided initial access to the cadaveric laboratory resources, ( $U=595$ ,  $p<0.05$ ). There were no significant differences observed between groups on quiz #2, after participants had accessed both learning resource modalities. Further, no significant differences were observed in performance between question categories across assessments or between learning

modalities. Mean percent performance across spatial anatomy knowledge assessments is displayed in Figure 12.



**Figure 12: Mean percent score across assessment subsequent to access to learning resource modalities (cadaveric laboratory vs 3D e-learning); (Mean  $\pm$  SD; n=87). \* indicates a significant difference within a group in spatial anatomy knowledge assessment scores at  $p<0.01$ . # indicates a significant difference between groups in spatial anatomy knowledge assessment scores within a single assessment at  $p<0.05$ . Participants in Group A are shown in grey and initially accessed the cadaveric resources. Participants in Group B are shown in purple initially accessed the 3D e-learning resources.**

**Table 3: Descriptive statistics across spatial anatomy knowledge assessments subsequent to access to e-learning resource modalities for undergraduate medicine participants.**

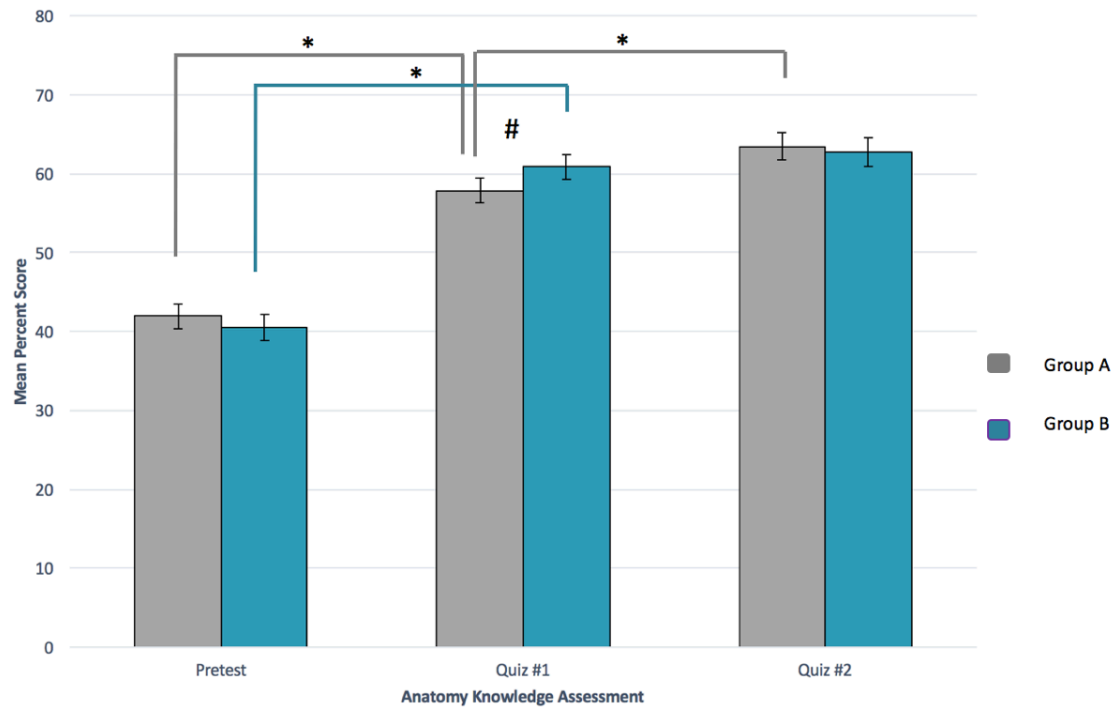
	Mean (% $\pm$ SEM)	Median (%)	Q1 (%)	Q3(%)
Baseline Spatial Anatomy Knowledge Assessment				
Group A (2D $\rightarrow$ 3D)	47.85 $\pm$ 1.52	45.45	33.33	51.52
Group B (3D $\rightarrow$ 2D)	48.99 $\pm$ 2.13	42.42	32.58	48.48
Spatial Anatomy Post-Knowledge Assessment #1				
Group A (2D $\rightarrow$ 3D)	61.31 $\pm$ 1.94	56.76	51.35	67.57
Group B (3D $\rightarrow$ 2D)	68.92 $\pm$ 2.21	62.16	54.05	70.27
Spatial Anatomy Post-Knowledge Assessment #2				
Group A (2D $\rightarrow$ 3D)	67.70 $\pm$ 2.24	66.67	53.79	72.73
Group B (3D $\rightarrow$ 2D)	68.63 $\pm$ 2.67	63.64	51.52	72.73

### 3.3.2 Evaluation of 3D E-Learning Resource within the Undergraduate Systemic Human Anatomy Course

Study data were analyzed using R statistical software, version 3.2.2. (R Core Team 2013). Analysis began with the calculation of descriptive statistics for the mean percent scores for each of the baseline, quiz #1 and quiz #2 assessments. The normality of the data was also assessed using the Shapiro-Wilk test for normality, which revealed a significant departure in the data from normality,  $W=0.9691$ ,  $p=0.025$ . As the data significantly deviated from normality, further analysis of the data utilized non-parametric measures. A summary of the descriptive statistics are shown in Table 4.

To examine potential difference between and within participant groups, Mann-Whitney U tests with a continuity correction were performed on mean percent assessment scores both within and across learning resource modalities. Participants in both Group A and Group B significantly improved their performance between the baseline and quiz #1 knowledge assessments respectively ( $W=125.5$ ,  $p<0.01$ ;  $W=26$ ,  $p<0.01$ ). Additionally, participants in Group A who accessed the 3D e-learning resource following exposure to the 2D e-learning resource, significantly improved their mean percent performance on quiz #2 ( $W=688$ ,  $p<0.01$ ), however no significant result was observed for participants in Group B who accessed the 2D e-learning resources following exposure to the 3D e-learning resource.

Analysis between groups utilized the Mann-Whitney U tests with no significant differences observed between groups on the baseline knowledge assessment or spatial ability as measured by the Santa Barbara Solids Test scores. Comparison between the groups revealed a significant difference between mean percent scores on quiz #1, with participants who initially accessed the 3D e-learning resource performing better than participants who were provided initial access to the 2D e-learning resources, ( $U=2095$ ,  $p<0.047$ ). There were no significant differences observed between groups on quiz #2, after participants had accessed both learning resource modalities. Further, no significant differences were observed in performance between question categories across assessments or between learning modalities. Mean percent performance across spatial anatomy knowledge assessments is displayed in Figure 13.



**Figure 13: Mean percent score across assessment subsequent to access to learning resource modalities (2D e-learning vs 3D e-learning); (Mean  $\pm$  SD; n=144). \*** indicates a significant difference within a group in spatial anatomy knowledge assessment scores at  $p < 0.01$ . # indicates a significant difference between groups in spatial anatomy knowledge assessment scores within a single assessment at  $p < 0.01$ . Participants in Group A are shown by grey markers and initially accessed the 2D e-learning resources. Participants in Group B are represented in blue and initially accessed the 3D e-learning resources.

**Table 4: Descriptive statistics across spatial anatomy knowledge assessments subsequent to access to e-learning resource modalities for undergraduate allied health sciences participants.**

	Mean (% $\pm$ SEM)	Median (%)	Q1 (%)	Q3(%)
Baseline Spatial Anatomy Knowledge Assessment				
Group A (2D $\rightarrow$ 3D)	41.92 $\pm$ 1.57	45.45	33.33	51.52
Group B (3D $\rightarrow$ 2D)	40.49 $\pm$ 1.61	42.42	32.58	48.48
Spatial Anatomy Post-Knowledge Assessment #1				
Group A (2D $\rightarrow$ 3D)	57.51 $\pm$ 1.57	56.76	51.35	67.57
Group B (3D $\rightarrow$ 2D)	61.45 $\pm$ 1.53	62.16	54.05	70.27
Spatial Anatomy Post-Knowledge Assessment #2				
Group A (2D $\rightarrow$ 3D)	63.64 $\pm$ 1.72	66.67	53.79	72.73
Group B (3D $\rightarrow$ 2D)	62.75 $\pm$ 1.87	63.64	51.52	72.73

### 3.4 Discussion

Historically, neuroanatomy has been a challenging topic in the anatomy curriculum for many novice students in the allied health sciences, which as has been partially attributed to the complexity of spatial relationships between brain structures (Ridsdale, Massey, and Clark 2007; Zinchuk et al. 2010). The evaluations of the interactive 3D neuroanatomy learning resource, that incorporates design features to facilitate cognitive load reduction, demonstrated significant improvements in students' spatial neuroanatomy knowledge for students enrolled in both undergraduate and professional level anatomy courses. Further, this beneficial impact on learning was observed both when students utilized the resource prior to and following access to conventional learning resources. These results provide support to past studies that have reported the beneficial impact of 3D educational technologies on student learning in neuroanatomy (Drapkin et al. 2015; Estevez, Lindgren, and Bergethon 2010; Pani, Chariker, and Naaz 2013; Ruisoto Palomera, Juanes Méndez, and Prats Galino 2014b).

While this study evaluated the impact of the addition of a 3D e-learning tool in both an undergraduate and professional degree level courses, similar results have also been observed at the graduate study level. The addition of a 3D e-learning resource in a semester-long graduate-level neuroanatomy course has been reported to significantly improve students' knowledge of neuroanatomy, particularly on laboratory examinations (Peterson and Mlynarczyk 2016). As the learning resource was implemented over the duration of the semester, these results suggest that the incorporation of 3D learning resources may be beneficial to the long-term retention of neuroanatomy information in addition to the short-term learning outcomes evaluated in this study. Similarly, the addition of an interactive e-learning resource for neuroanatomy, has been found to be an effective teaching tool for training medical students' skills for the interpretation of magnetic resonance imaging of brain structures. By providing students with the opportunity to transition between 2D MRI images and a 3D model, with the possibility to overlay the 3D representation on the MRI images, students significantly improved their knowledge of C-shaped subcortical structures (Drapkin et al. 2015).

The significant improvements in performance on a spatial neuroanatomy knowledge assessment in this study, following exposure to the 3D e-learning resource, provides further evidence that 3D visualizations may facilitate participants' ability to identify and locate neuroanatomy structures. This may be due to an improved ability of the participants to create accurate and complete mental representation of the brain structures and their spatial relationships. Educational theories suggest such improvements could be attributed to the 3D learning resources serving as a framework to assist in the development of mental representation, and consequently reduce the level of cognitive load experienced by novice students while learning spatial neuroanatomy when compared to conventional, 2D learning resources (Mayer 2005).

With ongoing reform and modernization of anatomy curricula, including a continuing trend of reduction in the amount of lecture and laboratory instruction time (Drake et al. 2009; McBride and Drake 2018), as well as dramatic increase in the development of educational technologies available, it is essential that efficacious and efficient tools be integrated within curricula to best support students learning. Evaluations of e-learning resources have not yielded consistent results, with some reporting contrasting results to this study, with no advantageous effects of the specific 3D technologies observed. The neutral or negative effects on learning of some 3D e-learning resources may be a result of the differences in the design of the learning resources, the methods of implementation of the resources, or the anatomical content included within the modules. The results of studies investigating the effect of 3D resources on student learning of the carpal bones failed to show a positive impact on learning imparted by the 3D models (Garg et al. 1999; Garg et al. 2002; Garg, Norman, and Spero 2001). Specifically in the area of neuroanatomy, a study evaluating the effect of a 3D virtual reality tool for teaching surface brain anatomy reported a negative impact of an interactive 3D resource on student learning, as compared to a passive-view of predetermined key views (Levinson et al. 2007).

One factor that could have contributed to the conflicting results is the greater spatial complexity of the subcortical neural structures taught in this study in comparison to the carpal bones and the surface brain structures examined in the other studies. This was



acknowledged as a limitation by some previous studies, with authors noting their neutral findings may be caused by the reduced spatial complexity existing in the spatial relationships investigated in their studies (Garg et al. 1999). Additionally, positive results have been observed in past studies that have applied 3D learning tools into the curricula of anatomical regions of high spatial difficulty (Glittenberg and Binder 2006; Nicholson et al. 2006; Yeung, Fung, and Wilson 2011).

A second consideration for the discrepancies in the observations of studies evaluating the effectiveness of educational technologies is the differences in the designs of the learning resources. The e-learning resources deployed in this study were guided by several principles described in the Multimedia Learning Theory to support the reduction of extraneous cognitive load experienced by learners during their interactions with the resources, including the multimedia, spatial contiguity, and signaling principles. Another study examining the use of an augmented-reality learning tool for the neural pathways which utilized similar principles for cognitive load reduction, reported both lower cognitive load as measured by the Cognitive Load Scale, as well as significant improvements on an anatomy knowledge test as compared to a traditional 2D resource (Küçük, Kapakin, and Göktaş 2016). The design of the e-learning resources in this study promoted active engagement by the participants due to features that enabled manipulation of the participants' viewpoint within any of the three planes of view (x, y, and z), adjustment of the level of magnification to ease in viewing smaller neural structures, as well as interactive roll-over labels visible with the position of the mouse over desired regions. Past studies have provided support to this view by demonstrating increased levels of knowledge and retention when students engage in active learning strategies in comparison to superficial learning techniques (Hahm et al. 2007; James et al. 2002; McManus et al. 1998; Rhem 1995).

### 3.4.1 Study Limitations

Due to pre-assigned laboratory groups, participants enrolled in the undergraduate medicine Neuroanatomy, Eye, and Ear course, the two learning modality groups were not matched based on factors including age, gender, or visuospatial ability. To address the possible effect of such variables, baseline measurements were completed to quantify

incoming knowledge of spatial neuroanatomy as well as spatial ability, with neither assessment revealing significant differences between the two experimental groups. Further analysis could be performed to evaluate the potential correlation between pretest score values and performance on post-module knowledge assessments, to determine if participants with high and low levels of prior knowledge were impacted differently by each learning modality. Due to the integrated nature of the anatomy curricula, and absence of a full course in neuroanatomy for either student populations studies, investigation of the impact of the 3D e-learning resource focused on evaluating the short-term impact of the resource on learning outcomes. Further evaluation of the effect of the 3D resource on students' long-term retention of a spatial neuroanatomy knowledge would be beneficial for understanding the potential of such educational techniques for improving learning outcome over the course of pre-clinical training, as well as its potential impact on trainees' confidence level and performance in a clinical setting.

### 3.5 Conclusions

The results of this study support previous evidence of the beneficial impact of integrating 3D e-learning resources for improvement of students' anatomical knowledge, especially for the understanding of spatially complex relationships in the area of neuroanatomy that are often limited with the use of conventional resources such as cadaveric dissection and 2D images and illustrations. As a significant number of novice students and medical trainees continue to express neurophobic attitudes towards their level of knowledge and confidence in the clinical neurological sciences, it is essential that improvements are made to existing curricula, in order to modulate these negative learning experiences and increase the number of confident and competent professionals who are able to ensure a high level of care for future patients.

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## Chapter 4

### 4 Influence of Spatial Ability on Learning Spatial Neuroanatomy

This chapter describes the assessment of the relationship between individual differences in spatial ability and successful achievement of learning outcomes in spatial neuroanatomy when utilizing an interactive 3D, web-based e-learning resource. The potential relationship between spatial ability and degree of success on spatial neuroanatomy learning outcomes was investigated in both undergraduate medicine and third-year undergraduate systemic human anatomy student populations.

#### 4.1 Factors in Learning Spatial Information

The modern classroom, either digital or physical in nature, is an environment rich in naturally-occurring and artificial objects designed to assist in students' learning. The Theory of Distributed Cognition outlines how cognitive tasks involved in learning require students to process information that exists both as internal mental representations and external objects in their environment (Zhang and Norman 1994). In distributed cognitive tasks, external resources are not merely redundant learning supplements, but rather they are essential components of the representational system, that in combination with internal representations form the structure of the task (Zhang and Norman 1994). As a result, task performance in anatomy is dependent upon a balance between the internal resources such as schemas and mental images in conjunction with external resources available to the student such as physical models and specimens, 2D images, and 3D virtual models or simulations. External resources help shape and guide cognitive processes during a task, and have the capacity to change the nature and difficulty of a given task (Mayer 2005; Zhang and Norman 1994). Depending upon the characteristics of both the student as well as the external resource utilized, the extent of the task that is reliant on internal representations may increase or decrease. For students who experience difficulty forming adequate internal representations, the efficacy of external resources may be of greater importance, due to their increased dependence upon external representations while completing the task.



The evolution and expansion of external resources available, including e-learning technologies, has enhanced the ability to present and communicate spatial anatomical information in formats ranging from static visual representations, to dynamic and interactive images and models (Trelease 2016). These image modalities differ in the amount of spatial anatomical information and the method by which such information is presented (Mayer 2005). While static images are frequently used to portray anatomical structures in a key view, similar to those included in anatomy textbooks or atlases, dynamic visualizations can portray an increased level of depth and complex spatial properties by providing multiple perspectives. Further research is needed to elucidate how 3D e-learning representations may affect the nature of distributed cognitive tasks while learning spatially-complex topics such as neuroanatomy.

The learning of spatial information utilizes a sub-component of working memory termed visuospatial working memory (Miyake et al. 2001), and the efficacy of processing visual information in visuospatial working memory is largely influenced by one's level of spatial ability. Spatial ability refers to a multifaceted skill set that measures an individual's ability to represent, transform, create and retrieve visual information (Linn and Petersen 1985). Further research in the field of cognitive psychology has identified spatial visualization (Vz), spatial orientation (SO) and spatial rotations (SR) as the principle components of spatial ability. Of particular interest to medical educators is Vz, which has been defined as the ability to process, encode and mentally transform spatial relationships in 2D and 3D dimensions (Carroll 1993), and is involved in many learning tasks in anatomy. In order to evaluate the impact of spatial ability in different learning situations, individuals' spatial ability must be quantified, which have prompted the development of several validated instruments including the Mental Rotations Test (MRT) (Vandenberg and Kuse 1978), and the Santa Barbara Solid Test (SBST) (Cohen and Hegarty 2012).

## 4.2 Relationship between Spatial Ability and Success in Anatomy Education

Spatial ability has received considerable attention in education psychology research, especially in anatomical and medical education, due to the evidence provided by several studies that have identified a relationship between spatial ability level and both clinical skills acquisition (Abe et al. 2017; Brandt and Davies 2006; Shafqat et al. 2015; Smith et al. 2012) and anatomy knowledge acquisition (Lufler et al. 2012; Nguyen, Nelson, and Wilson 2012). Pioneering work in the topic reported a significant relationship between low spatial ability and poor performance in anatomy among university students (Rochford 1985). Further research has reported a significant positive correlation between success on a test of spatial anatomical knowledge of the wrist joint, and students' level of spatial ability (Garg et al. 1999). Similarly, students with high spatial ability have been shown to be more successful than students with low spatial ability on practical anatomy assessments (Khot et al. 2013), with students who possess high spatial ability being more than twice as likely to score above ninety percent on practical examinations in a gross anatomy course (Lufler et al. 2012).

A fundamental category of anatomical tasks requiring spatial ability is the inference of 3D structural representations from cross-sectional 2D images. This specific task is essential for success in many anatomy topics, including neuroanatomy, as students must frequently interpret cross-sectional illustrations and clinical imaging modalities of 3D structures. As with other aspects of spatial anatomy knowledge, success in this method of anatomy assessment has been found to significantly correlate with performance on tests of spatial ability (Langlois et al. 2017). A study evaluating anatomical learning as measured by ability to identify anatomical structures in 2D cross-sectional images, as well as localization of the cross-sectional images within a key plane of view, reported a significant positive relationship between spatial ability and performance on both assessments (Luursema et al. 2006). Further evidence to support this relationship was reported in a recent study that utilized a novel spatial anatomy task that involved a combination of mental rotation and transformation of anatomical structures, identification of 2D cross-sectional images, and localization of planes corresponding to specific cross-

sections. In this study, Vz was positively correlated with performance on the task, and negatively correlated with the duration of time required to complete the assessment (Nguyen, Nelson, and Wilson 2012).

With the increased integration of 3D e-learning visualizations, it is of growing importance to elucidate if such 3D visualizations could modify the impact of Vz ability levels on the successful development of spatial anatomy knowledge, and thus minimize the effect of individual differences in spatial ability on determining student success. Studies in cognitive psychology have provided evidence of the malleability of spatial cognitive skills (Uttal et al. 2013), with the potential for improvement by low spatial ability individuals with engagement in spatial ability training exercises. Increases in spatial ability have been reported for students enrolled in spatially-complex programs including geology (Titus and Horsman 2009), chemistry (José and Williamson 2008), and anatomy (Lufler et al. 2012; Vorstenbosch et al. 2013b). This finding is of significance for anatomy education considering that while high spatial ability is beneficial for learning anatomy, a reciprocal relationship may exist by which learning anatomy also enhances spatial ability. By developing and implementing resources such as 3D interactive models to support spatially challenging topics such as anatomy, there may be the potential to not only improve understanding of spatial anatomy of low spatial ability students, but also to improve their spatial skill set for enable greater success in future spatial assessments and performance of spatially-complex clinical skills.

## 4.3 Methodology

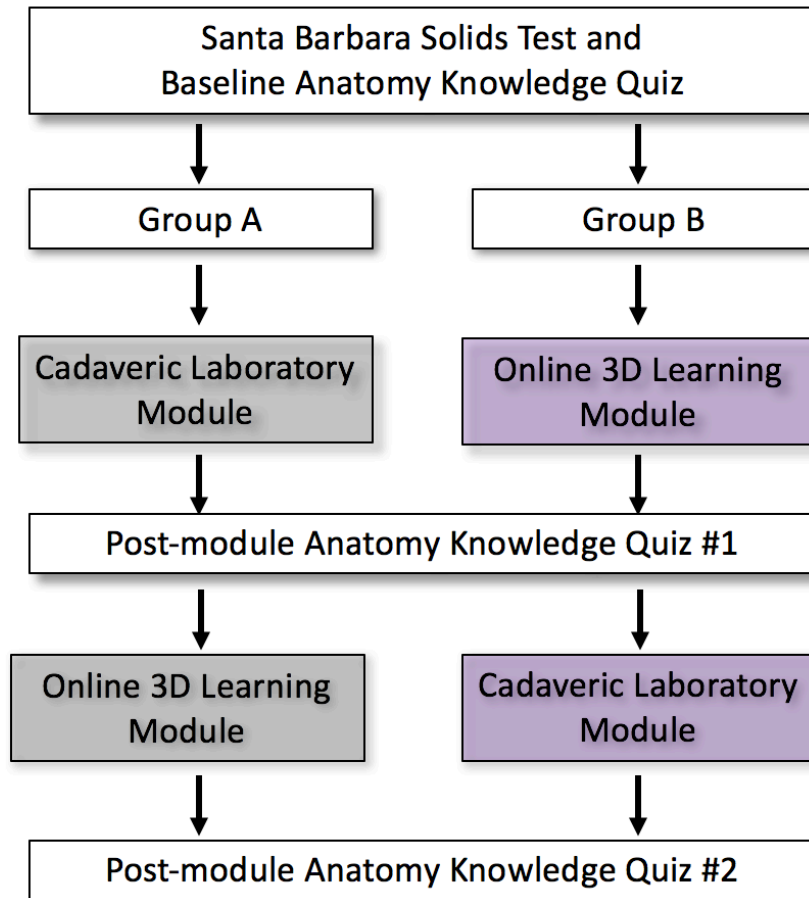
### 4.3.1 Study Population

The aim of this research was to evaluate the potential relationship between spatial ability, as measured by performance on the SBST of spatial ability, and performance on a multiple-choice format quiz of spatial neuroanatomy knowledge collected from two distinct student populations, specifically students enrolled in the undergraduate medicine program, and third-year undergraduate systemic human anatomy course as a component of a degree in the health sciences. A total of eighty-seven students in the medicine program, and one hundred forty-four students enrolled in the undergraduate systemic

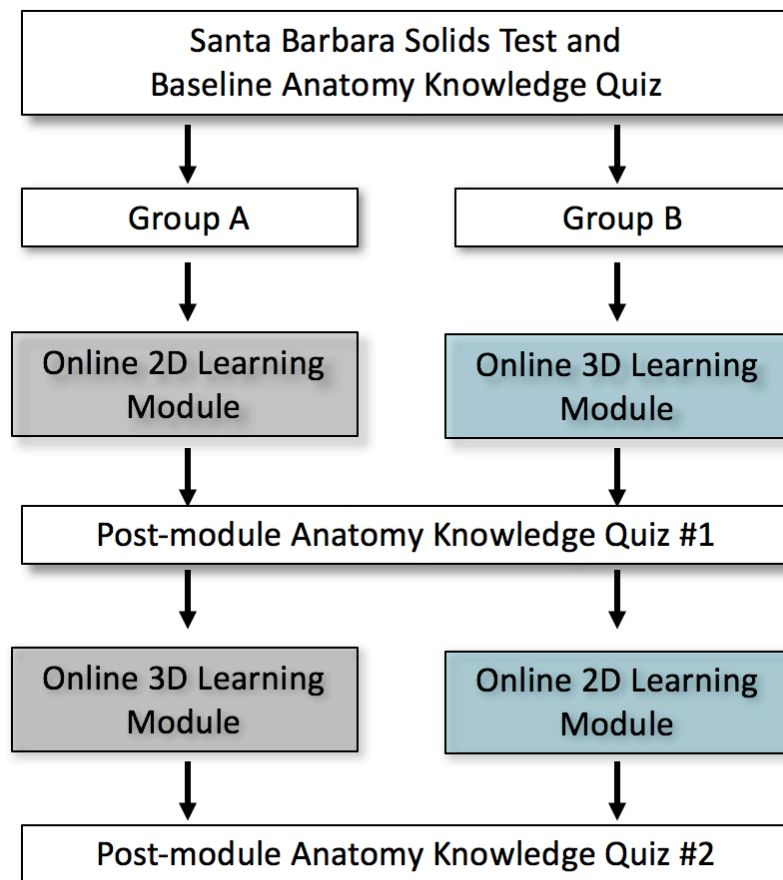
anatomy course complete all components of the study. Students were ranked based on their incoming level of spatial ability, as measured by the Santa Barbara Solids Test of spatial ability. Participants with an odd ranking were assigned to Group A, and those with an even ranking of spatial ability were assigned to Group B. All components of this study were approved by the Research Ethics Board at Western University #104870 (Appendix A) and all participants provided informed consent prior to their involvement in the study.

#### **4.3.2 Study Design for Investigation of Relationship between Spatial Ability and Anatomy Assessment Performance**

The evaluation of the relationships between spatial ability level and performance on the spatial neuroanatomy knowledge assessment utilized a randomized cross-over experimental design for both student populations. Participants were ranked based on their Santa Barbara Solids Test scores and randomly assigned to one of two experimental groups, which both accessed the learning resources, however the order in which they accessed these resources was reversed. Participants with odd rankings were assigned to Group A, and those with even rankings were assigned to Group B. The cross-over design alternated the order the exposure to learning modalities between groups in the undergraduate medicine and undergraduate human systemic anatomy student populations as shown in Figure 14 and 15 respectively. Evaluations of the potential relationships between the spatial ability and spatial anatomy knowledge scores were completed following exposure to each of the learning resources.

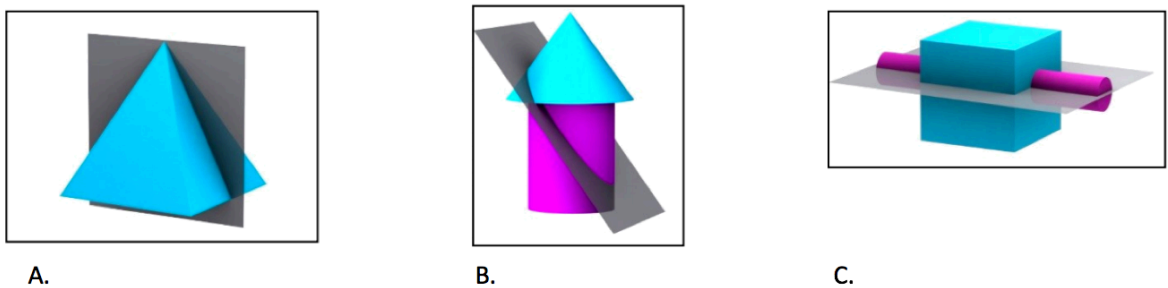


**Figure 14: Schematic diagram of the pseudorandomized cross-over study design utilized with the undergraduate medicine student population. Participants were assigned to Group A or B based on the random assignment of student laboratory groups by course instructors at the beginning of the academic year.**



**Figure 15: Schematic diagram of the pseudorandomized cross-over study design utilized with the undergraduate third-year level systemic human anatomy course. Participants were assigned to Group A or B based on the random assignment.**

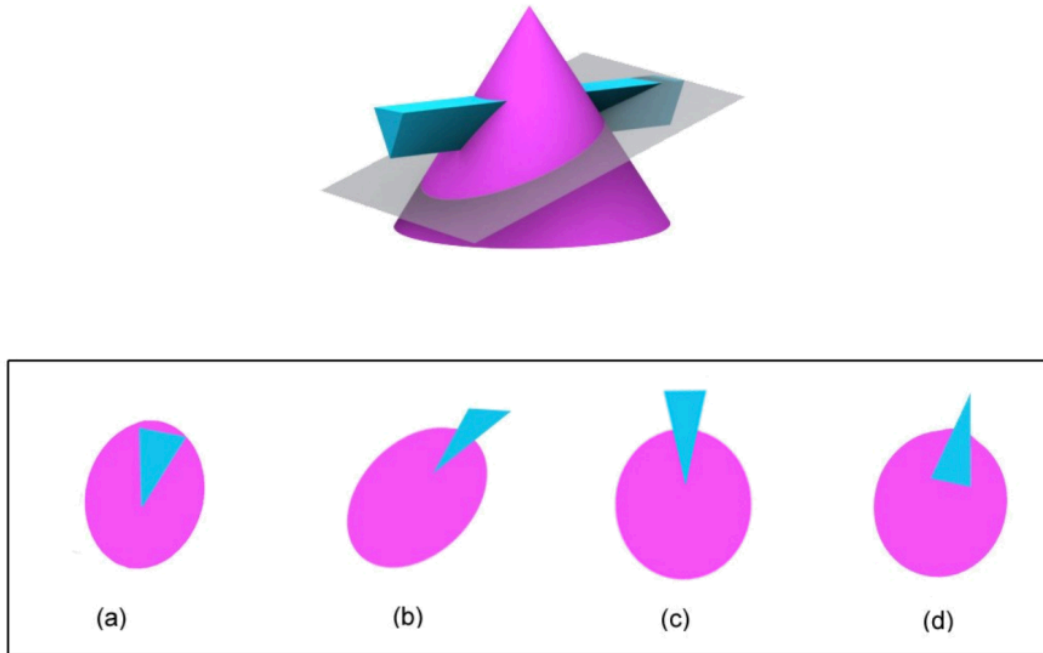
The measurement tool utilized to provide a baseline score of participants' spatial ability was the SBST (Cohen and Hegarty 2012). This test of spatial ability utilizes a set of thirty questions of 3D geometric shapes of varying complexity from individual basic shapes, to attached objects composed of basic geometric shapes that have been joined, to the most complex category which include shapes that have been embedded within larger shapes. All objects were divided by a single transecting plane of varying orientations (horizontal, vertical, or oblique). Examples of each type of object and transecting plane utilized within the SBST are displayed in Figure 16.



**Figure 16: A) The geometric shape in this question utilizes a single object with a transecting vertical plane. B) The geometric object is transected by an oblique plane and is classified as an attached object, as two basic shapes are connected on their edges. C) The geometric object is transected by a horizontal plane, and is classified as a nested object as one basic shape, the pink cylinder, is contained within the second basic shape, the blue cube.**

In order to successfully complete this multiple-choice format test, participants were required to identify which of the displayed images was produced when the 3D object was cut by the plane shown, from four possible answer choices. The instructions also explicitly stated the participants were to select the image that would be produced when standing directly in front of the plane, which in several questions required the mental transformation of the image provided. Each correct response was awarded a point for a maximum possible score of 28 points. A representative example of an assessment

question displaying a nested object with and oblique transecting plane and the four associated response alternatives is demonstrated in Figure 17.



**Figure 17: A representative question from the Santa Barbara Solid Test of spatial ability. This is an example of a nested object as one geometric object is embedded within a larger geometric shape that have been transected by an oblique plane. Participants were instructed to select the image that would be observed when standing directly in front of the plane cutting the image. The correct response for this example is image “c”.**

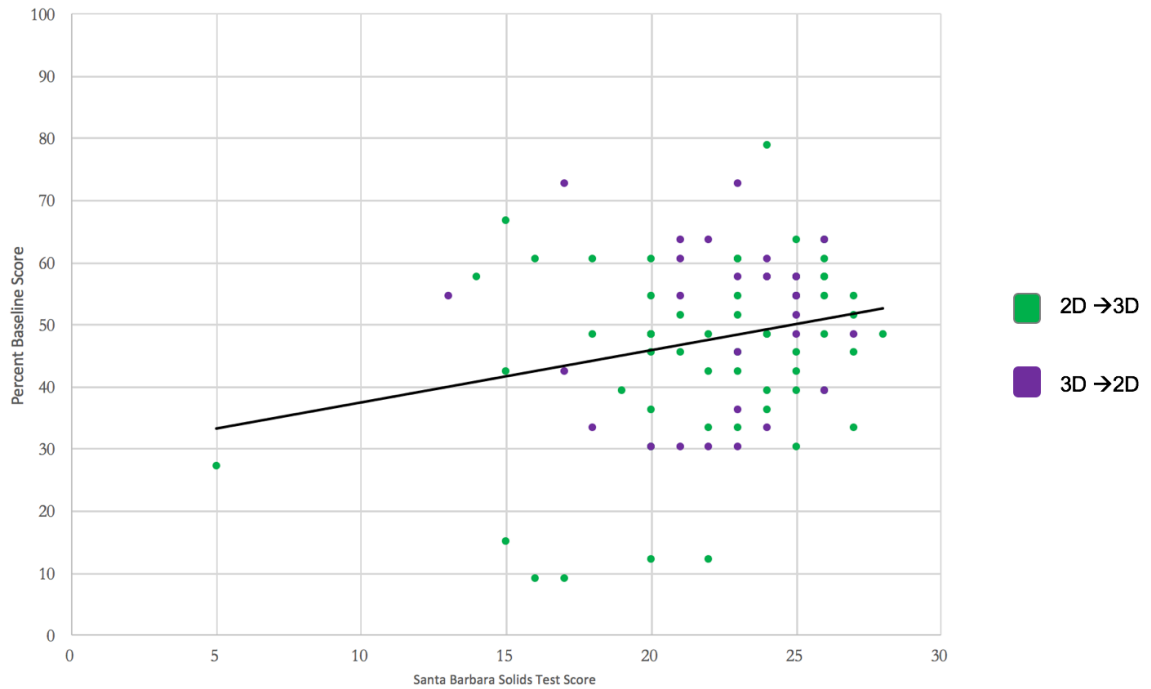


## 4.4 Results

### 4.4.1 Evaluation of the Relationship between Spatial Ability and Spatial Neuroanatomy Knowledge Scores

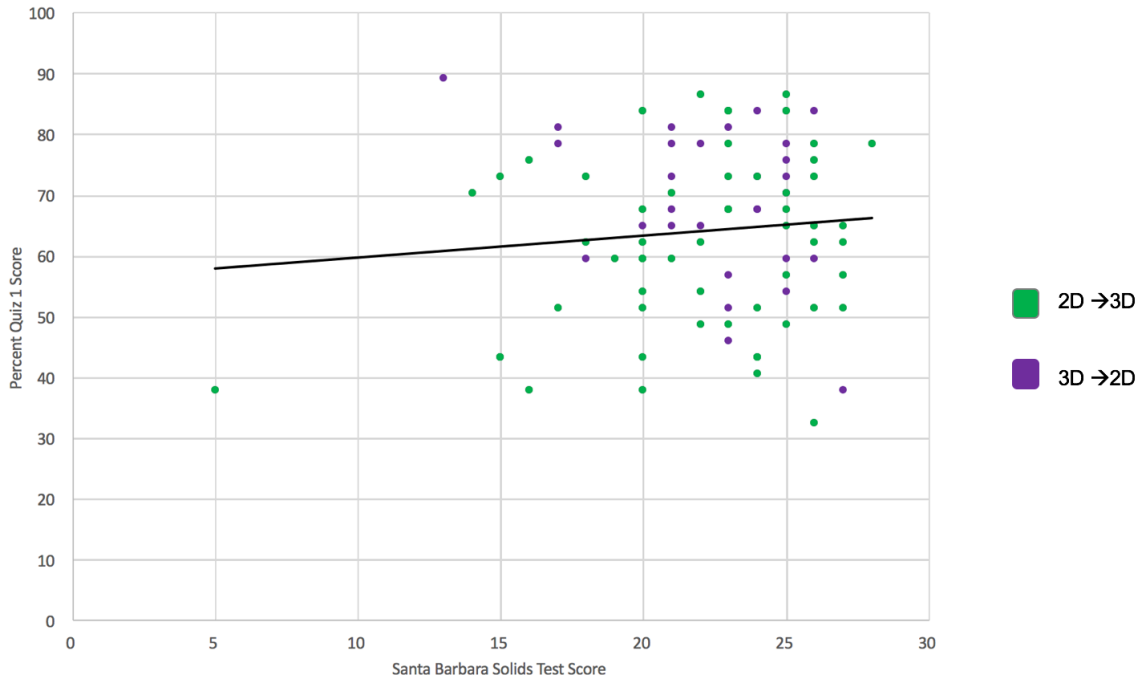
Study data were analyzed using R statistical software, version 3.2.2.(R Core Team 2013). The normality of the data was initially assessed using the Shapiro-Wilk test for normality, which revealed a significant departure in the data from normality,  $W=0.9791$ ,  $p=0.029$ . As the data significantly deviated from normality, further analysis of the data utilized non-parametric measures.

Analysis first examined potential relationships for the undergraduate medicine student population, utilizing the Spearman Rank Correlation test ( $r_s$ ). As shown in Figure 18, a significant, weak positive relationship was observed between participants' baseline spatial anatomy knowledge and score of spatial ability on the SBST ( $r_s = 0.23$ ,  $p=0.03$ ). Further analysis was performed to evaluate potential sex differences in spatial ability between male and female participants. The mean ( $\pm$  SD) Santa Barbara Solids Test score of spatial ability were calculated separately for male and female participants ( $21.43 \pm 4.75$  and  $22.06 \pm 3.08$  respectively). A Mann Whitney U test to evaluate potential sex differences in spatial ability found no significant differences were observed between the two groups ( $W=828$ ,  $p=0.41$ ), so no further analysis across sexes was performed.



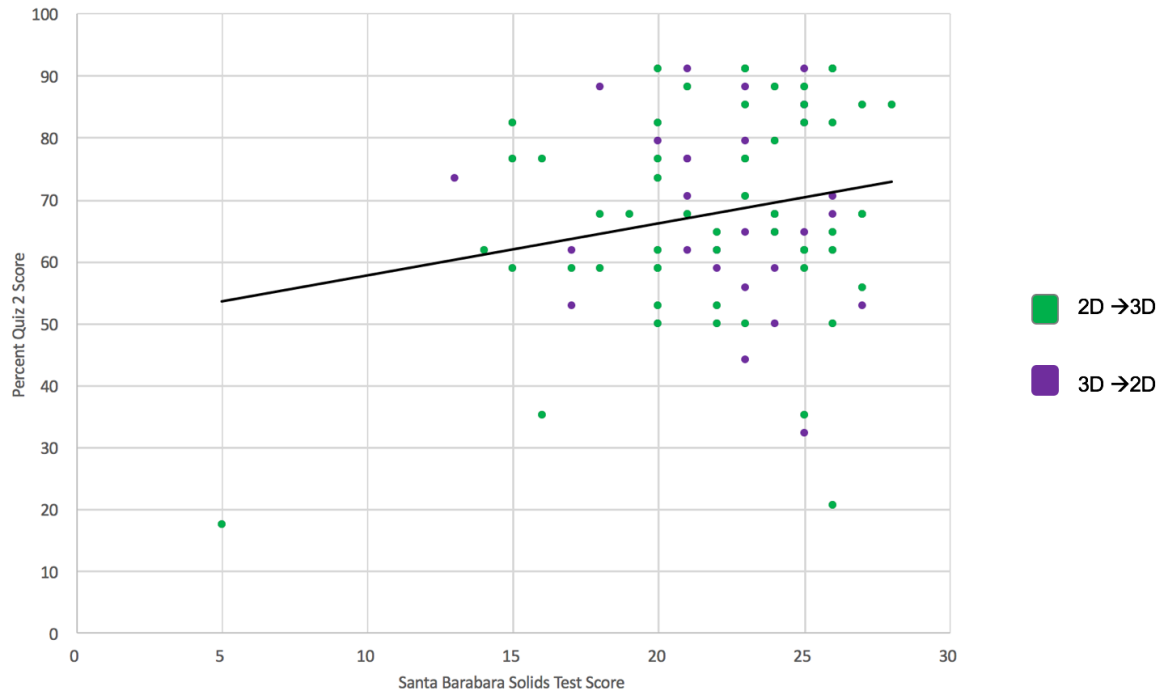
**Figure 18: A significant positive correlation between scores on the Santa Barbara Solids Test of spatial ability and percent score on the baseline assessment for spatial neuroanatomy knowledge was observed ( $r_s = 0.23$ ,  $p = 0.03$ ;  $n = 87$ ). Participants in Group A are shown by grey markers and initially accessed the cadaveric resources. Participants in Group B are shown by purple markers and initially accessed the 3D e-learning resources.**

Potential relationships were then examined between spatial ability and spatial anatomy knowledge assessment (Quiz #1) scores proceeding interactions with the first learning module, as shown in Figure 19. A weak positive trend continued to be observed between the two variables for all participants ( $r_s = 0.11$ ,  $p > 0.05$ ), however there was no significant relationship observed between spatial ability and spatial anatomy knowledge scores on the Quiz #1 assessment.



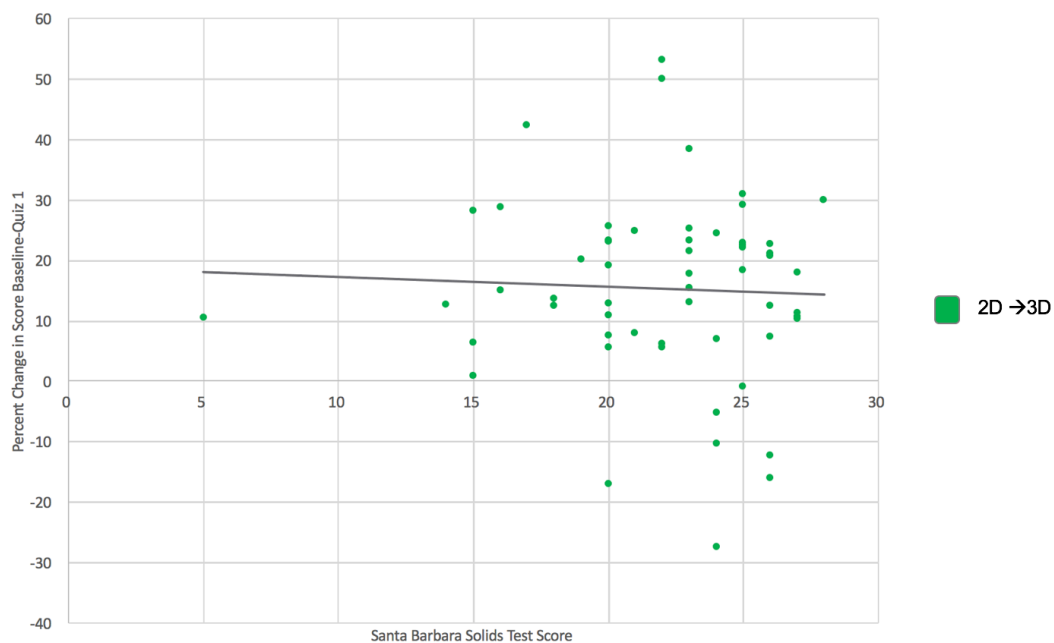
**Figure 19: No significant relationships were observed between scores on the Santa Barbara Solids Test of spatial ability and percent score on the first post-module (Quiz #1) assessment for spatial neuroanatomy knowledge ( $r_s = 0.11$ ,  $p > 0.05$ ;  $n = 87$ ). Participants in Group A are shown by grey markers and initially accessed the cadaveric resources. Participants in Group B are shown by purple markers and initially accessed the 3D e-learning resources.**

Relationships were then examined between spatial ability and spatial anatomy knowledge assessment (Quiz #2) scores following interactions with the second learning module, as shown in Figure 18. As shown in Figure 20, a significant, weak positive relationship was observed between participants' post-module spatial anatomy knowledge scores on the second post-module quiz (Quiz #2) and their score of spatial ability on the SBST ( $r_s = 0.26$ ,  $p = 0.02$ ).



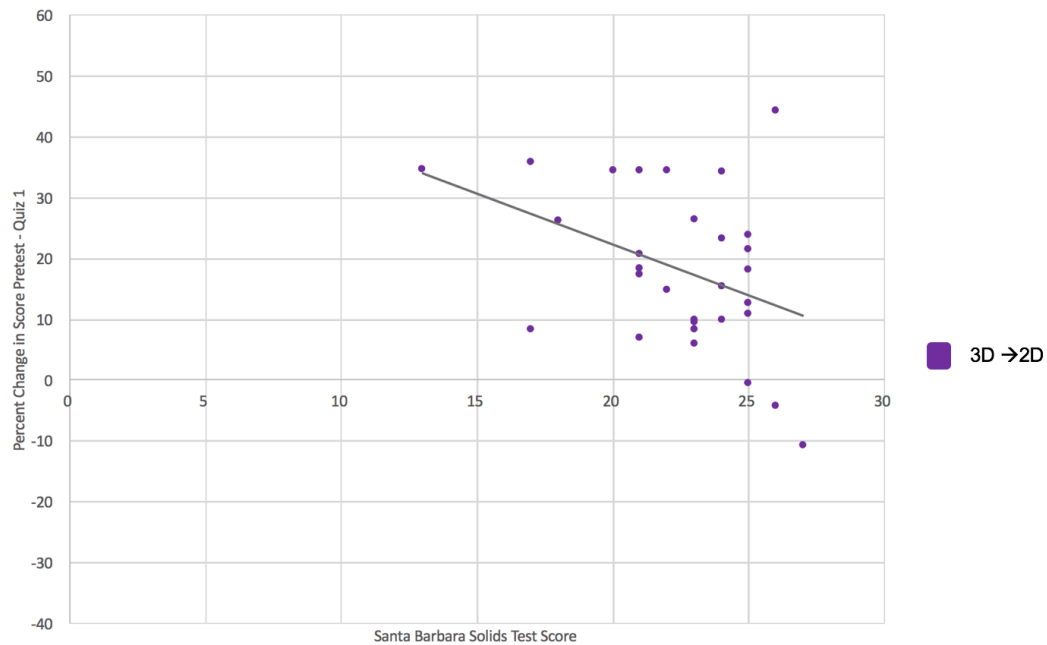
**Figure 20: A significant positive correlation between scores on the Santa Barbara Solids Test of spatial ability and percent score on the second post-module (Quiz #2) assessment for spatial neuroanatomy knowledge was observed ( $r_s = 0.26$ ,  $p = 0.02$ ;  $n = 87$ ). Participants in Group A are shown by grey markers and initially accessed the cadaveric resources. Participants in Group B are shown by purple markers and initially accessed the 3D e-learning resources.**

Further evaluation of the associations between the performance scores on assessments of anatomy knowledge and spatial ability investigated connection between the changes recorded in participants' percent score between assessments and their level of spatial ability. The Spearman rank correlation was calculated for each learning modality group, and revealed no significant relationship between percent change in score between baseline anatomy knowledge and performance on the first post-module anatomy knowledge assessment for participants who initially accessed the cadaveric laboratory resources ( $r_s = -0.02$ ,  $p > 0.05$ ), as shown in Figure 21.



**Figure 21: For participants in group A who initially accessed the cadaveric laboratory resource, there was no significant relationship observed between scores on the Santa Barbara Solids Test of spatial ability and percent change in score on the first post-module (Quiz #1) assessment for spatial neuroanatomy knowledge ( $r_s = -0.02$ ,  $p > 0.05$ ;  $n = 50$ ).**

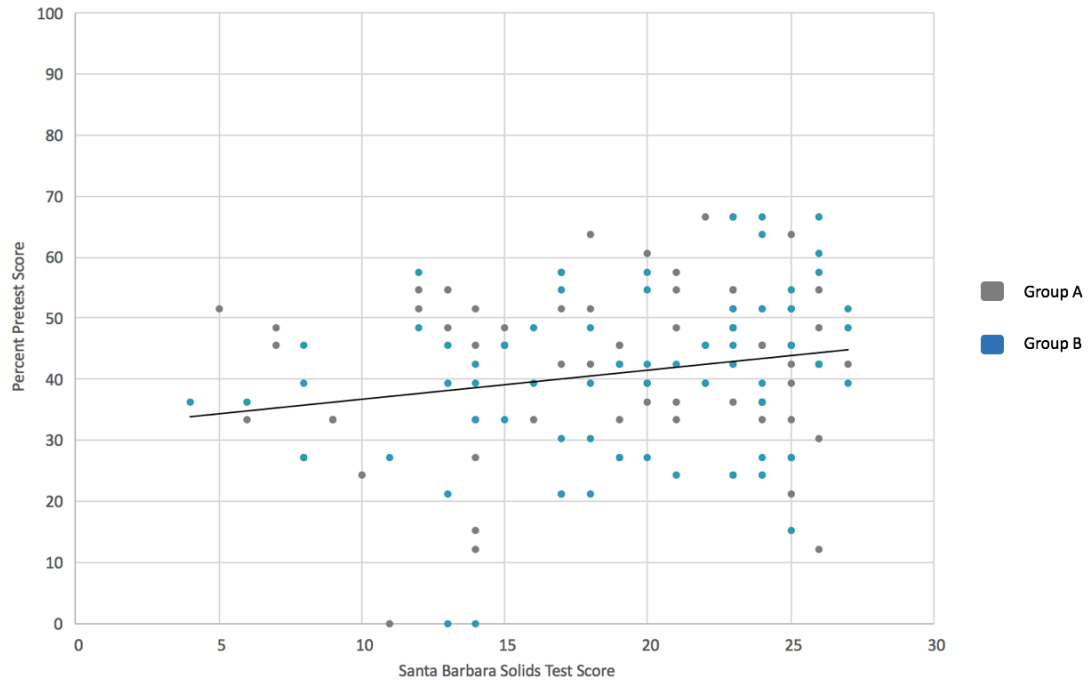
When the same type of analysis was performed for participants in Group B, who initially accessed the 3D e-learning resource, a significant negative correlation was observed between participants' percent change in score on the neuroanatomy spatial knowledge assessments and their level of spatial ability ( $r_s = -0.37$ ,  $p = 0.044$ ), as displayed in Figure 22.



**Figure 22: For participants in group B who initially accessed 3D e-learning resource, there was significant negative relationship observed between scores on the Santa Barbara Solids Test of spatial ability and percent change in score on the first post-module (Quiz #1) assessment for spatial neuroanatomy knowledge ( $r_s = -0.37$ ,  $p=0.044$ ;  $n=37$ ).**

Subsequent analysis sought to determine if these findings were limited to the first population studied, or similar results were more general and could be observed in an undergraduate student population enrolled in a systemic anatomy course, without a dissection component of instruction. Similar to the observations within the undergraduate medicine student population, the mean ( $\pm$  SD) Santa Barbara Solids Test score of spatial ability were calculated separately for male and female participants ( $19.19 \pm 5.63$  and  $19.26 \pm 5.93$  respectively). A Mann Whitney U test to evaluate potential sex differences in spatial ability found no significant differences were observed between the two groups ( $W=2367$ ,  $p=0.80$ ), so no further analysis across sexes was performed.

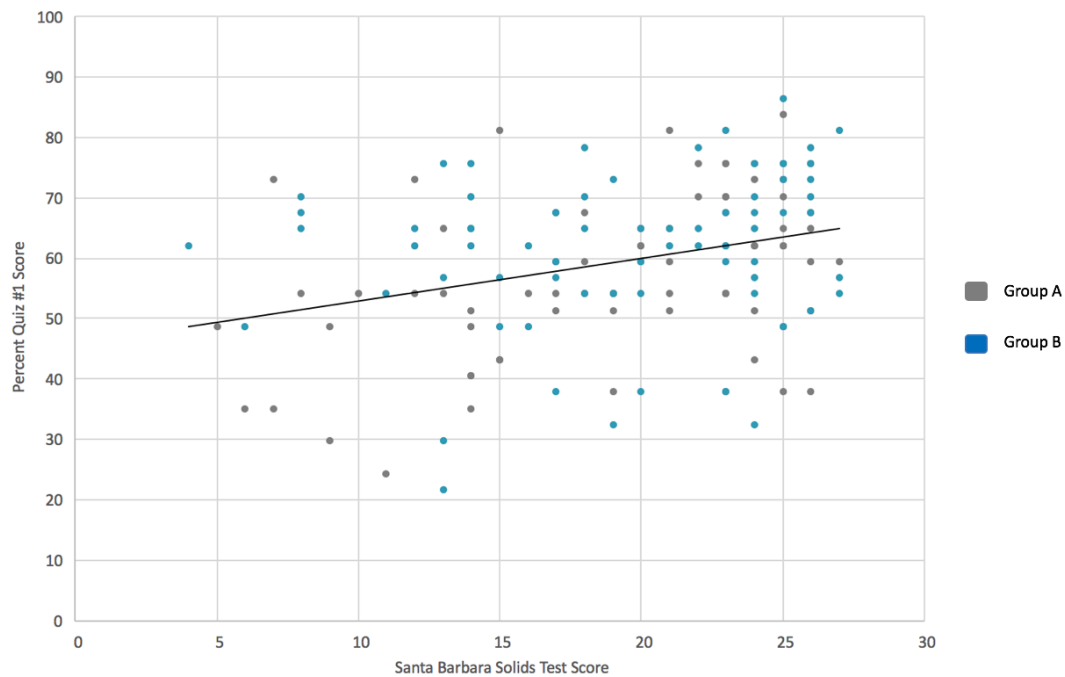
As the potential relationships for the undergraduate health sciences student population data also included significant departures from normality,  $W=0.9691$ ,  $p=0.025$ , non-parametric analysis was once again performed to measure potential relationships between variables. Utilizing the Spearman Rank Correlation test ( $\rho$ ), as shown in Figure 23, a significant, a weak positive relationship was observed between participants' baseline spatial anatomy knowledge and score of spatial ability on the SBST ( $r_s=0.21$ ,  $p=0.01$ ).



**Figure 23: A significant positive correlation between scores on the Santa Barbara Solids Test of spatial ability and percent score on the baseline assessment for spatial neuroanatomy knowledge was observed ( $r_s = 0.21$ ,  $p = 0.01$ ). Participants in Group A are shown by grey markers and initially accessed the conventional 2D e-learning resources. Participants in Group B are shown by blue markers and initially accessed the 3D e-learning resources.**

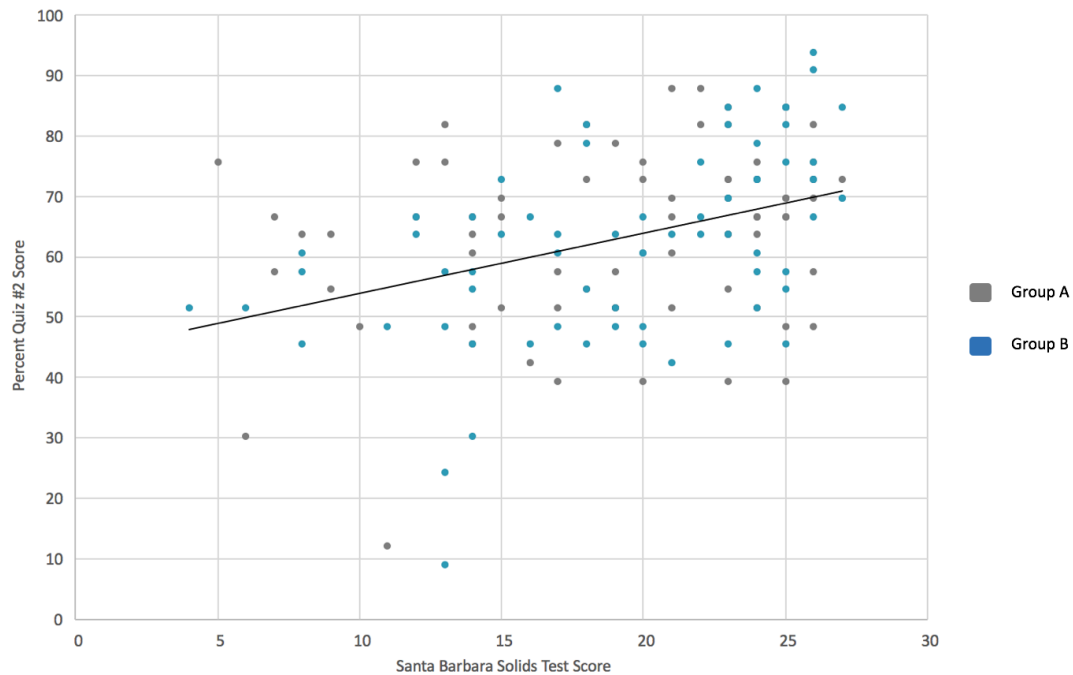


Potential relationships were then examined between spatial ability and spatial anatomy knowledge assessment (Quiz #1) scores proceeding interactions with the first learning module, as shown in Figure 24. A weak, but significant, positive relationship continued to be observed between spatial ability and spatial anatomy knowledge scores for all participants ( $r_s = 0.31$ ,  $p < 0.01$ )



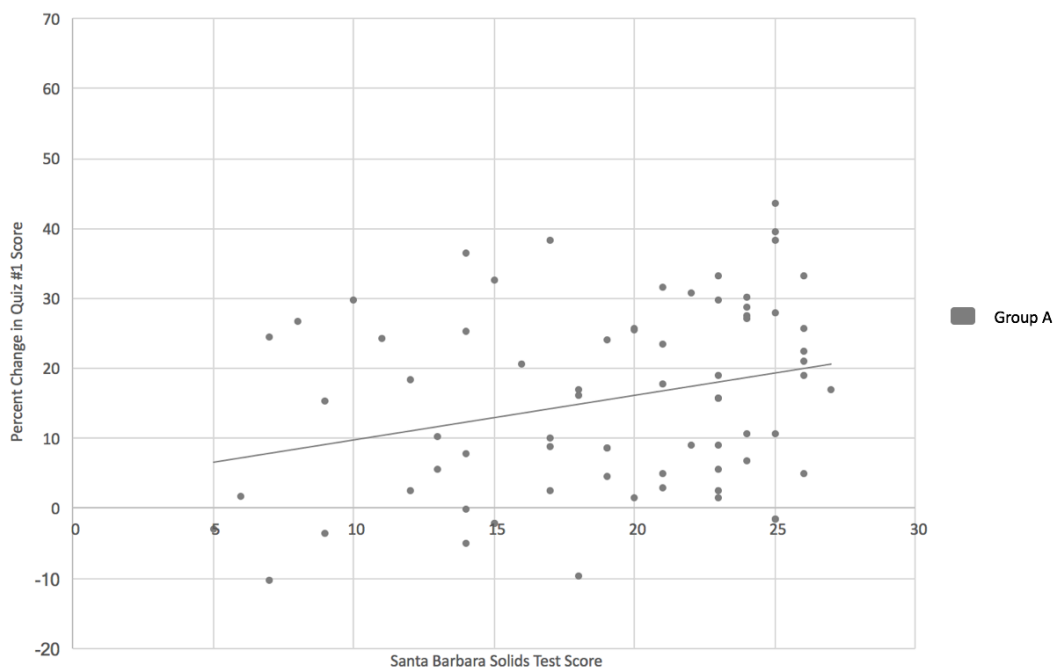
**Figure 24: A significant positive correlation between scores on the Santa Barbara Solids Test of spatial ability and percent score on the first post-module assessment for spatial neuroanatomy knowledge (Quiz #1) was observed ( $r_s = 0.31$ ,  $p < 0.01$ ). Participants in Group A are shown by grey markers and initially accessed the conventional 2D e-learning resources. Participants in Group B are shown by blue markers and initially accessed the 3D e-learning resources.**

Relationships were then examined between spatial ability and spatial anatomy knowledge assessment (Quiz #2) scores proceeding interactions with the second learning module, as shown in Figure 25. A significant, weak positive relationship was observed between participants' post-module spatial anatomy knowledge scores on the second post-module quiz (Quiz #2) and their score of spatial ability on the SBST ( $r_s = 0.38$ ,  $p < 0.01$ ).



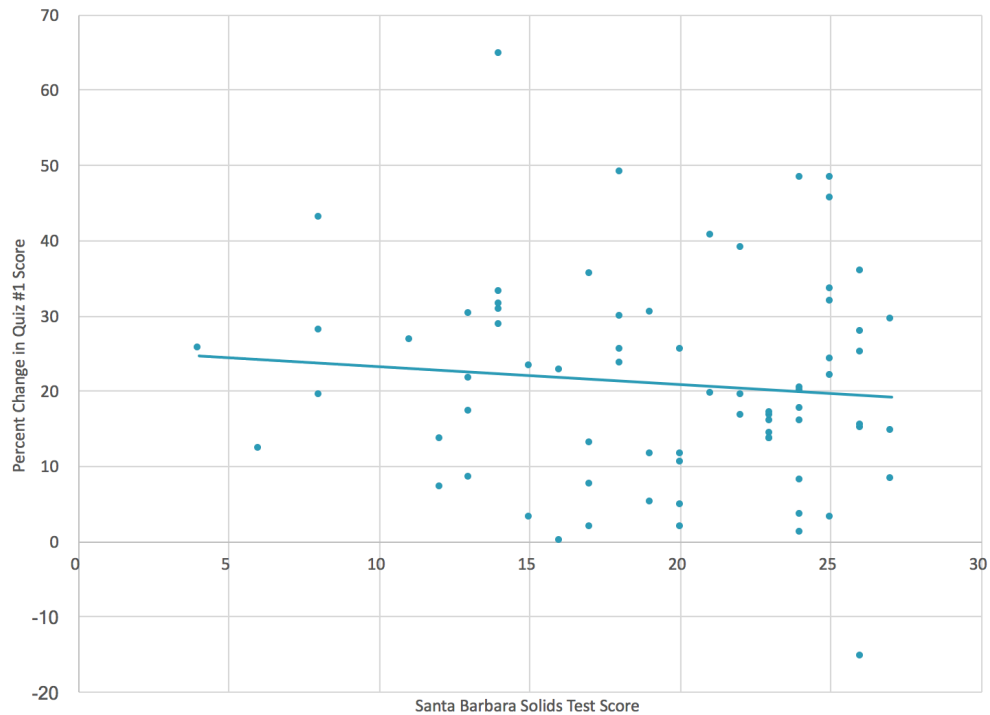
**Figure 25: A significant positive correlation between scores on the Santa Barbara Solids Test of spatial ability and percent score on the second post-module assessment for spatial neuroanatomy knowledge (Quiz #2) was observed ( $r_s = 0.38$ ,  $p < 0.01$ ). Participants in Group A are shown by grey markers and accessed the conventional 2D e-learning resources, whereas participants in Group B are shown by blue markers and initially accessed the 3D e-learning resources.**

Further evaluation of the associations between the performance scores on assessments of anatomy knowledge and spatial ability investigated a potential connection between the changes recorded in participants' percent score between assessments and their level of spatial ability. The Spearman rank correlation was calculated for each learning modality group, and revealed a significant positive relationship between spatial ability and the percent change in score across the baseline and first post-module anatomy knowledge assessments for participants in Group A, who initially accessed conventional 2D e-learning resources. ( $r_s = 0.28$ ,  $p = 0.02$ ), as displayed in Figure 26.



**Figure 26:** For participants in group A who initially accessed the conventional 2D e-learning resources, there was a significant positive relationship observed between scores on the Santa Barbara Solids Test of spatial ability and percent change in score on the first post-module (Quiz #1) assessment for spatial neuroanatomy knowledge ( $r_s = 0.28$ ,  $p = 0.017$ ).

When the same analysis was performed for participants in Group B, who initially accessed the 3D e-learning resource, a negative trend was observed between participants' percent score on assessments of spatial ability and neuroanatomy spatial knowledge ( $r_s = -0.10$ ,  $p > 0.05$ ), as displayed in Figure 27.



**Figure 27: For participants in group B who initially accessed 3D e-learning resources, there was negative trend observed between scores on the Santa Barbara Solids Test of spatial ability and percent change in score on the first post-module (Quiz #1) assessment for spatial neuroanatomy knowledge ( $r_s = -0.10$ ,  $p > 0.05$ ).**

## 4.5 Discussion

Past studies investigating the factors affecting success in neuroanatomy education have revealed a positive relationship between an individual's level of spatial ability and their resulting success in learning anatomy (Rochford 1985;Guillot et al. 2007;Fernandez, Dror, and Smith 2011;Lufler et al. 2012; Langlois et al. 2017). The results of this study provide further support to this hypothesis, with weak positive correlations observed between participants' spatial ability scores and their performance on several of the post-modules assessment of spatial neuroanatomy knowledge. The weak correlations observed may have been partially attributed to the incorporation of 3D e-learning resource, which may be acted as a scaffold for participants to build upon their spatial knowledge with less reliance on their spatial cognitive skills (Mayer, 2005). When potential associations between spatial ability and changes in anatomy assessment scores were investigated for participants who utilized conventional learning resources, significant positive correlations were observed for both the medicine and undergraduate student populations. Further, when the percent change in score was correlated with students' spatial ability for participants provided initial access to the 3D e-learning resource, there was a significant negative correlation observed between spatial ability and change in assessment score for students in the undergraduate medical program. A negative trend was also observed in the relationship between spatial ability and change in anatomy assessment score for students in the undergraduate health science student population. The negative correlation in the undergraduate medicine student populations suggest that learning outcomes of low spatial ability students improved more from the interactions with the 3D resources than students with high spatial ability scores. These results lend additional support to past studies that have reported an amplified benefit of 3D educational technologies on student learning anatomy particularly for students with low spatial ability (Luursema et al. 2006;Brewer et al. 2012;Berney et al. 2015;Cui et al. 2017).

There has yet to be a clear consensus reached regarding the role of spatial ability in learning anatomy, which may be partially attributed to the inconsistent, highly variable assessment methods utilized. Studies using either essay, or non-spatial knowledge assessments have reported non-significant correlations between spatial ability and

assessment scores (Rochford 1985; Hoyek et al. 2009; Keedy et al. 2011). In contrast, positive significant correlations have been observed in studies employing assessments involving 3D synthesis from 2D images (Garg et al. 2002), student drawing of anatomical viewpoints (Provo, Lamar, and Newby 2002; Cohen and Hegarty 2007), interpretation of cross-sectional images (Provo, Lamar, and Newby 2002; Luursema et al. 2006, 2008; Stull, Hegarty, and Mayer 2009; Nguyen et al. 2014), mental rotations of structures (Nguyen et al. 2014; Stull, Hegarty, and Mayer 2009), or practical examinations (Rochford 1985; Lufner et al. 2012; Khot et al. 2013). Such differences across assessment formats may be linked to differences in the types of skills required to successfully complete each assessment category. Essay and non-spatial multiple-choice formatted assessments primarily evaluate an individual's linguistic ability to communicate functional and nominal factual knowledge. As a result, linguistic skills are not considered to be directly linked to spatial cognitive skills, providing a justification for the lack of correlations to spatial abilities on such assessment formats. Alternatively, the ability to encode, access and manipulate mental representation of spatial information is essential for successful completion of various assessment types composed of spatial questions or tasks, which is dependent on one's level of spatial ability. The positive correlations observed between spatial ability and anatomy knowledge assessment performance in this study, suggest the questions contained within the assessments effectively assessed students' knowledge of spatial relationship and characteristics, rather than their linguistic knowledge of the nominal characteristics of specific structures.

The results of this study, in combination with similar past findings, suggest that when provided with the correct resources to effectively support learning, the hindrance of low spatial ability can be mitigated, allowing for the successful development of mental representations of complex information such as neuroanatomical structures. Further, these results imply that although individuals with low spatial ability often experience difficulty in forming mental representation, once these representations have been developed, they possess good ability to mentally transform and manipulate these representations. In the final spatial neuroanatomy assessment (Quiz #2), students who interacted with the 3D e-learning resource improved their performance to a level that did not statistically differ from students who initially accessed the 3D e-learning resource,

with low spatial ability individuals specifically improving their assessment performance to a level equivalent to their high spatial ability peers. While measures of spatial ability may be valuable predictors of success in learning anatomy and other spatially-complex disciplines, these same measures could alternatively be used to identify student who may benefit most from the integration of additional visualizations such as 3D e-learning supports, and increase their probability of successfully acquiring spatial anatomy knowledge or clinical skills.

#### 4.5.1 Study Limitations

The SBST was selected as the measure of spatial ability in this study. While the test has been determined to be both a reliable and valid measure of spatial ability (Cohen and Hegarty 2012), there are a variety of other tests of spatial ability that have been used in some of the other studies discussed, with the MRT most frequently selected as the measure of spatial ability in these studies. The SBST was the lone measure of spatial ability utilized in the current experimental design, and consequently, the reliability and validity of the results reported could not be calculated between the SBST and other spatial ability tests. Further, the SBST was not repeated following the experimental period due to the short duration of the experimental period. Future studies could reassess the participants' spatial ability after utilizing both e-learning resources, to measure the potential impact of short-term exposure on spatial ability.

### 4.6 Conclusions

Successful learning and mastering of spatial anatomical information requires a combination of both internal and external spatial cognitive representations by novice students. As researchers and educators continue to investigate the impact of 3D visualizations, particularly as they influence the learning outcomes of individuals of varying spatial ability levels, it is critical to understand the characteristics and conditions necessary for these tools to be effective. In this study, we showed that spatial ability was positively correlated with successful spatial anatomy knowledge. Additionally, the advantageous effect of high spatial ability can be moderated with the integration of an interactive 3D e-learning resources for both medicine and undergraduate health science

neuroanatomy student populations. Further research into the efficacy of 3D e-learning resources should investigate how individual differences in spatial cognitive skills could predict which learners may receive the greatest benefit from these emerging educational technologies.



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## Chapter 5

### 5 Impact of Spatial Ability on Interactions with E-Learning Resources

This chapter describes the assessment of the relationship between individual differences in spatial ability and the potential patterns in interactions while utilizing interactive 3D and 2D, web-based e-learning resources to learn spatial relationships in neuroanatomy. The potential relationship between level of spatial ability and differences in interactions with the learning resources was investigated in a third-year undergraduate systemic human anatomy student population who were novices in the subject of neuroanatomy.

#### 5.1 Impact of Spatial Ability on Behaviours and Strategies used in Problem-Solving

An individual's spatial intelligence enables for the encoding and transformation of spatial information, and thus shapes the way they perceive objects encountered within their environment, as well as approaches they select when performing spatially-complex tasks. Such spatial tasks may range from routine activities like the interpretation of written directions to reach a desired location or driving a car, to highly specialized tasks such as solving advanced problems in mathematics or chemistry, or performing surgical procedures (Langlois et al. 2015). In area of anatomy education specifically, in addition to mastering correct terminology, novice students must learn spatial characteristics of structures including their shape, size and relative position to other structures. When performing clinical procedures, this spatial knowledge is essential, as internal structures such as the subcortical structures of the brain, are not directly visible. As a result, clinicians must rely on mental representations of the anatomical structures to successfully complete the given tasks. Successful performance in both anatomy courses, and clinical procedures have been shown to be positively correlated with spatial ability (Fernandez, Dror, and Smith 2011; Langlois et al. 2017; Lufner et al. 2012), with evidence of a reciprocal relationship between the two factors, in which experience in spatially-complex subjects has been shown to improve individuals' spatial ability (Guillot et al. 2007; Vorstenbosch et al. 2013a). However, it is less understood how differences in spatial

ability may be underpinning differences in behaviours and strategies utilized by individuals of high and low spatial ability, which contributes to the performance differences observed between these two groups.

A dominant theory of working memory postulates that working memory is a cognitive system that is responsible for the temporary storage and processing of limited capacity that may be subdivided into 3 principle components (Baddeley 1992). This theory suggests the existence of a central executive that primarily functions in attentional control, in addition to two components responsible for individualized processing of information of verbal and spatial modalities, and thus are referred to as verbal working memory (VWM) and visuospatial working memory (SWM) respectively. When simultaneously performing a primary and secondary task, often referred to as dual tasks, cognitive resources must be divided between the primary and secondary tasks (Fisk, Derrick, and Schneider 1986). When performance of a primary task occurs concurrently with a secondary task that competes for the same working memory resources, performance may be hindered due to the limited nature of working memory (Pashler 1994; Shah and Miyake 1996). Evidence to further support independent VWM and SWM entities has shown that as secondary task involving listening to a combination of spatial and non-spatial verbal descriptions while performing a primary verbal task interfered with the recall of both types of descriptions in the primary task. Conversely, performing a secondary spatial task only reduced the ability to recall spatial descriptions in the primary task (De Beni et al. 2005). Further analysis of the factors contributing to differences in performance on spatial ability tasks has suggested these variations may be reflective of differences in the processing speed of spatial information (Mumaw and Pellegrino 1984; Sims and Mayer 2002), capacity of SWM (Miyake et al. 2001), as well as strategies employed while encoding spatial information (Cohen and Hegarty 2007; Cohen and Hegarty 2012). As compared to their high-spatial ability peers, individuals with low spatial ability have been found to have slower processing speeds of spatial information, have a reduced SWM capacity, reducing the amount of spatial information they are able to store and process, as well as the utilization of less effective strategies when tasked with solving spatial problems (Miyake et al. 2001; Cohen and Hegarty 2007; Cohen and Hegarty 2012).

Preliminary evidence has also identified potential differences in strategies utilized by novice university students when solving spatially-complex problems (Rochford 1985). These strategies include sectioning (inference of a section that passes through a 3D object), translating (perception of an object's shape and orientation when rotated), rotating (maintenance of the mental representation of a structure relative to others while rotating the whole body), and visualizing (building new mental representations). There remains a lack of empirical evaluations of how such strategic differences may be the root of the observed differences in spatial anatomy task performance. While the impact of strategy selection is yet to be fully investigated in anatomy education specifically, research in other spatially-complex disciplines may provide insight to inform similar studies in the anatomical sciences. Students enrolled in organic chemistry differentially use strategies depending on their biological sex and spatial ability level (Stieff et al. 2012). Individuals with high spatial ability, and male participants report a preference to use mental imagery to assist in problem-solving whereas females and individuals with low spatial ability preference to use multiple strategies in addition to mental imagery including external diagrams and algorithms (Stieff et al. 2012).

Similarly, successful problem-solving of complex problems in mathematics is positively correlated with the use of mental representations to encode the spatial information. Conversely, a negative relationship was observed between performance for those participants who chose to employ pictorial representations that are dependent on the visual appearance of objects only, and not the spatial relationships that exist between structures (Hegarty and Kozhevnikov 1999). Similarly, evaluation of the problem-solving strategies utilized when solving kinematics questions in a university physics course revealed that high-spatial ability participants more frequently construct spatial representations that integrate multiple perspectives, with the ability to reorganize and transform the initial spatial schema into related representations to assist with solving novel problems. On the other hand, low spatial ability participants primarily construct pictorial representations with only a single perspective, and thus had to construct multiple unrelated representations to solve different spatial problems (Kozhevnikov, Motes, and Hegarty 2007).

Another area of research in acquisition of spatial information has focused on eye movements and fixations, or sustained periods of gaze, that have been linked to an individual's ability to process and learn spatial information (Carpenter 1988; Rayner 1998). It has been suggested that high spatial ability individuals may direct their attention to more essential characteristics of an object that are crucial to effective problem-solving (Lowe and Schnotz 2008; Roach et al. 2017a; Wolfe and Horowitz 2017). High spatial ability individuals have been found to have shorter fixation durations as compared to others with low spatial ability, while also attending to different regions of images in an electronic version of the MRT of spatial ability (Roach et al. 2017a). The differences in locations attended to between the groups were significant, with agreement in location of fixations occurring only thirty-four percent of the time (Roach et al. 2017a). These differences between the two groups are further heightened in timed-assessment situations (Roach et al. 2017b). These findings have direct implications in anatomy education, as many assessments are performed in time-limited, "bell-ringer" formats. As such it is important for educators to consider how students' level of spatial ability may affect their ability to understand and interpret spatial anatomy information under time pressures. In order to minimize the impact of individual differences in spatial ability between students, instructional and assessment strategies could be implemented to provide additional visualization support of spatial information, signaling of essential information to direct the focus of cognitive resources, and a reduction of time pressures to assist students with low-spatial ability.

## 5.2 Methodology

### 5.2.1 Study Population

The study recruited students enrolled in the third-year undergraduate systemic human anatomy course. A total of one hundred sixty-nine students completed all components of the study. Participants were ranked based on their Santa Barbara Solids Test scores and randomly assigned to one of two experimental groups, which both accessed the learning resources, however, the order in which they accessed these resources was reversed. Participants with odd rankings were assigned to Group A, and those with even rankings were assigned to Group B. During the experimental period, participants assigned to

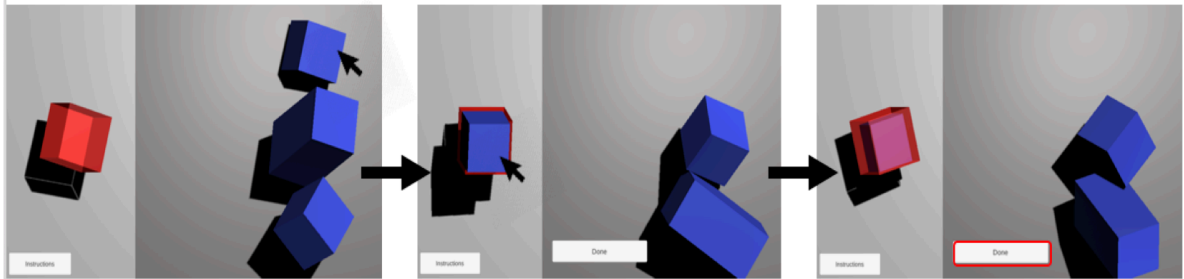


Group A were initially provided access to the conventional 2D e-learning resources, followed by access to the 3D e-learning resource. Conversely, participants in Group B were given access to the 3D e-learning resources initially, with subsequent access to the 2D e-learning modules. All components of this study were approved by the Research Ethics Board at Western University #104870 (Appendix A) and all participants provided informed consent prior to their involvement in the study.

### 5.2.2 Development of a Virtual Syncretion Assessment

In order to assess spatial knowledge in a method that was congruent with the format of the knowledge itself, a novel spatial task was developed. The task was termed a virtual syncretion task, which is guided by preliminary studies examining syncretion as an alternative approach to dissection when learning complex spatial information (Gangata 2008; Miller 2000). This theory suggests that when novice students are required to learn complex spatial anatomy using dissection methods alone, some fundamental principles of perception such as collinearity and symmetry may be difficult to observe with all anatomical structures present. Therefore, beginning with only a few main structures, and building the full model through placement of additional structures, may be more beneficial to learning (Miller 2000). While this instructional method has yet to be fully evaluated for its impact on learning of spatial information, preliminary findings report favourable student perceptions of such resources in a musculoskeletal laboratory curriculum (Gangata 2008). As neuroanatomy contains many complex spatial relationships between structures, which are often difficult to view in images or during the process of dissection, this particular topic in anatomy may be particularly well suited for learning the spatial relationships through syncretion methods. The virtual syncretion tasks utilized in this study required participants to place multiple neuroanatomy structures in their correct locations within partially assembled virtual 3D brain models. In order to assess participants ability to perform a task of placing a structure within another, all participants first completed two calibration tasks. These tasks used only basic geometric shapes to avoid the need for any specific anatomical knowledge to complete the task, and required the participants to select a shape, from multiple options presented, that could be placed within a larger red shape in a different location on the screen. To successfully

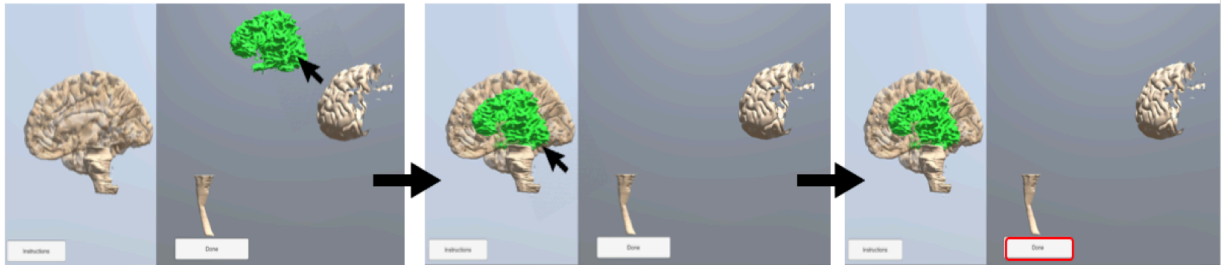
complete the task, the shape had to be selected and moved to a position within the larger shape. Participants could ensure they had placed the small shape correctly within the larger shape by rotating their viewpoint. A representational example of a calibration task is shown in Figure 28.



**Figure 28: Example of one of 2 calibration puzzles included in the virtual syncretion assessment for neuroanatomy spatial knowledge. Participants were required to select the correct shape from the three blue-coloured option on the right panel of the window. Once selected the shape was moved to the left panel of the window and placed within the larger red shape. When the participant determined the blue shape was positioned correctly, they clicked the “Done” button to complete the task.**

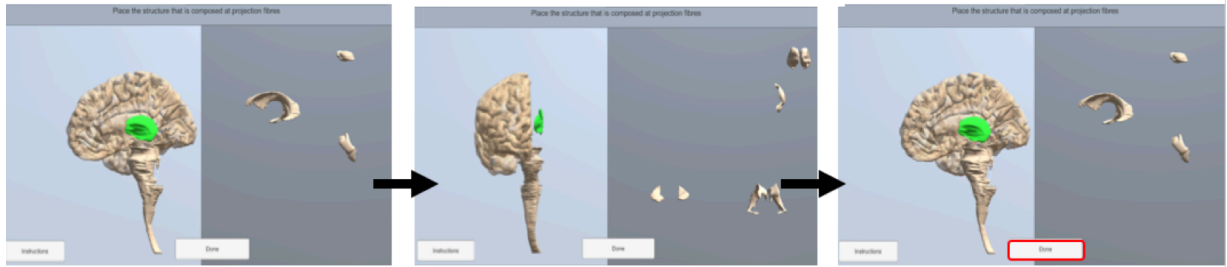
Once the calibration tasks had been completed, there were a total of four spatial neuroanatomy syncretion tasks included within each assessment. Participants were required to select each anatomical structure in an order of their choice, from the right panel of the screen view, then in the same manner as the calibration puzzle, select and move the structure to the left panel of the window, where a partial model of the brain was visible. The highlighting principle was utilized to indicate which structure had been selected by changing its colour to green. Once again, participants were able to confirm the placement of the structure was in their intended location by rotating the model and structures, which enabled them to assess their response from multiple perspectives. Once the participant had determined the structure was positioned in the perceived correct location, they clicked the “Done” button to begin placing another structure within the model. Each anatomy syncretion task, required the placement of five anatomical

structures. A representational example of a neuroanatomical syncretion task is shown in Figure 29.



**Figure 29: Example of one of four neuroanatomy syncretion tasks. Each task required the placement of five anatomical structures shown in the panel on the right of the screen within a partial model in the left panel of the screen. The highlighting principle was utilized to indicate the structure selected by changing its colour to green. Once all five structures had been placed, the task was considered to be complete.**

A final syncretion task involved a question-directed placement of neuroanatomy structures within a partial brain model. In this final task, students were required to select each anatomical structure in a specified order from the right panel, to correctly answer the question text presented at the top of the window. As in all other tasks, participants selected their chosen structure from a panel on the right side of the window, and moved this structure to the left side of the window to place it in the perceived correct location within a partial model. The consistent highlighting principle was utilized to indicate a selected structure by changing its appearance to green in colour. When the participant determined the position of the structure was correct, they clicked the “Done” button near the bottom of the screen to begin placing another structure based on a new text-based question. Once all seven structures in this portion were placed by the participant, the task was considered to be complete. A representational example of a question-based task is shown in Figure 30.



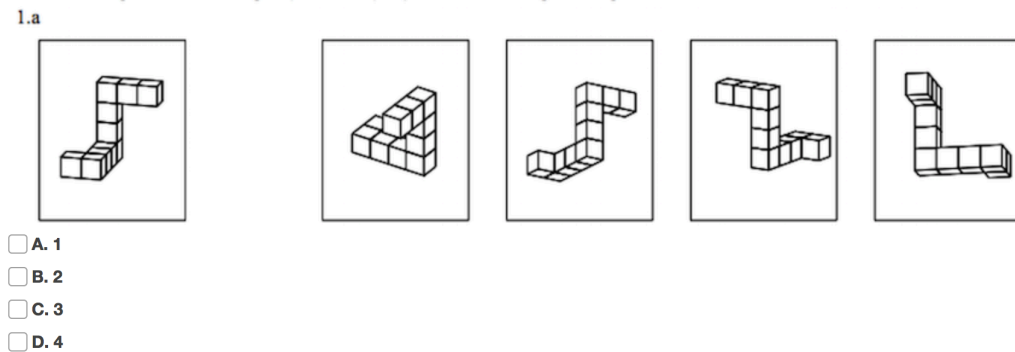
**Figure 30: Example of the placement of one structure within the question-based neuroanatomy syncretion task. This task required the placement of seven anatomical structures within the partial model in the left panel of the screen. The highlighting principle was utilized to indicate the structure selected by changing its colour to green. Once all seven structures had been placed, the task was considered to be complete.**

### 5.2.3 Study Design for Integration in Undergraduate Systemic Human Anatomy Course

The study sought to determine the potential differences between spatial ability and interactions with the 2D and 3D e-learning resources, as well as performance on the virtual syncretion task. All participants completed identical baseline assessments of spatial neuroanatomy knowledge, as well as the both the SBST and electronic version of the MRT as measures of spatial ability. Participants were randomly assigned to one of two experimental groups, Group A or Group B, prior to accessing the first of two e-learning resources. Participants appointed to Group A were given initial access to an e-learning module composed of 2D e-learning resources containing 2D anatomical images, and descriptive text, whereas participants assigned to Group B were provided with initial access to an e-learning module composed of a 3D neuroanatomy model and descriptive text. Following exposure to the initial learning modality (2D or 3D e-learning), all participants completed a second twenty-five question assessment of their spatial neuroanatomy knowledge (Post-module Anatomy Knowledge Quiz #1) and Virtual Syncretion Task #1. After completion of both assessments, participants were provided with subsequent access to the second e-learning resource. Similar to the procedure with

the first learning resource, students were asked to utilize the resource to master the learning objectives, and were able to end their interactions with the learning resource at their own discretion when they believed they had sufficiently learned the information. A final twenty-five question spatial neuroanatomy knowledge assessment (Post-module Anatomy Knowledge Quiz #2) and virtual syncretion task (Virtual Syncretion Task #2) was administered following participants exposure to the second learning modality to assess its impact on student learning.

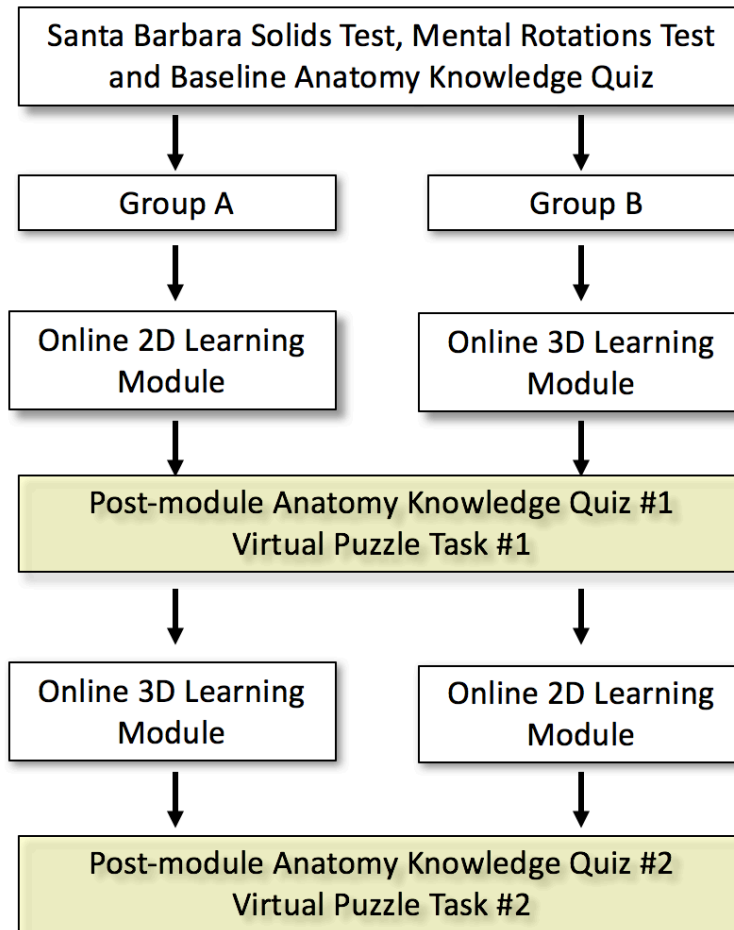
A second measurement tool, the Mental Rotations Test (MRT), was utilized to provide an additional score of participants' spatial ability. This test of spatial ability utilizes a set of twenty-four questions which each contain a single stimulus on the left that is in the form of 3D geometric shape of varying structure and orientation. In addition to the stimulus, each question presents four alternative geometric shapes, two of which are rotated versions of the stimulus on the left. The other two figures presented display figures that are structurally different from the stimulus on the left. A representative example of a question utilized within the MRT is displayed in Figure 31.



**Figure 31: An exemplar of a question contained within the Mental Rotations Test (MRT). To successfully answer each question, the participants must select the two images on the right that are rotated versions of the initial stimulus on the left.**

In order to successfully complete this multiple-choice format test, participants were required to identify which two of the displayed images were rotated versions of the initial stimulus that had been presented, from four possible answer choices. The instructions also explicitly stated the participants were provided with only six minutes to complete as many of the questions contained within the test as possible before time expired. One point was assigned for each correct selection, for a possible of score of 2 per question, and a maximum total score of twenty-four points.

All components of the integration of the 3D resource into the undergraduate systemic anatomy course were completed online, with all user interaction data recorded for each session. Data collected during interactions with both the 3D and 2D e-learning resources included the frequency with which structures were selected from the interactive menu, movement of the mouse within the virtual space of the resources, and length of time spent accessing each of the online resources. Data for the manipulation of the position and rotation of the model was also collected exclusively for participants' interactions with the 3D e-learning resource. A schematic diagram of the methodology followed for evaluation of the 3D e-learning resource when integrated in to the undergraduate systemic human anatomy course curriculum is shown in Figure 32.



**Figure 32: Schematic diagram of the pseudorandomized cross-over study design utilized with the undergraduate third-year level systemic human anatomy course. Participants were assigned to Group A or B based on the random assignment of student laboratory groups by course instructors at the beginning of the academic year.**

## 5.3 Results

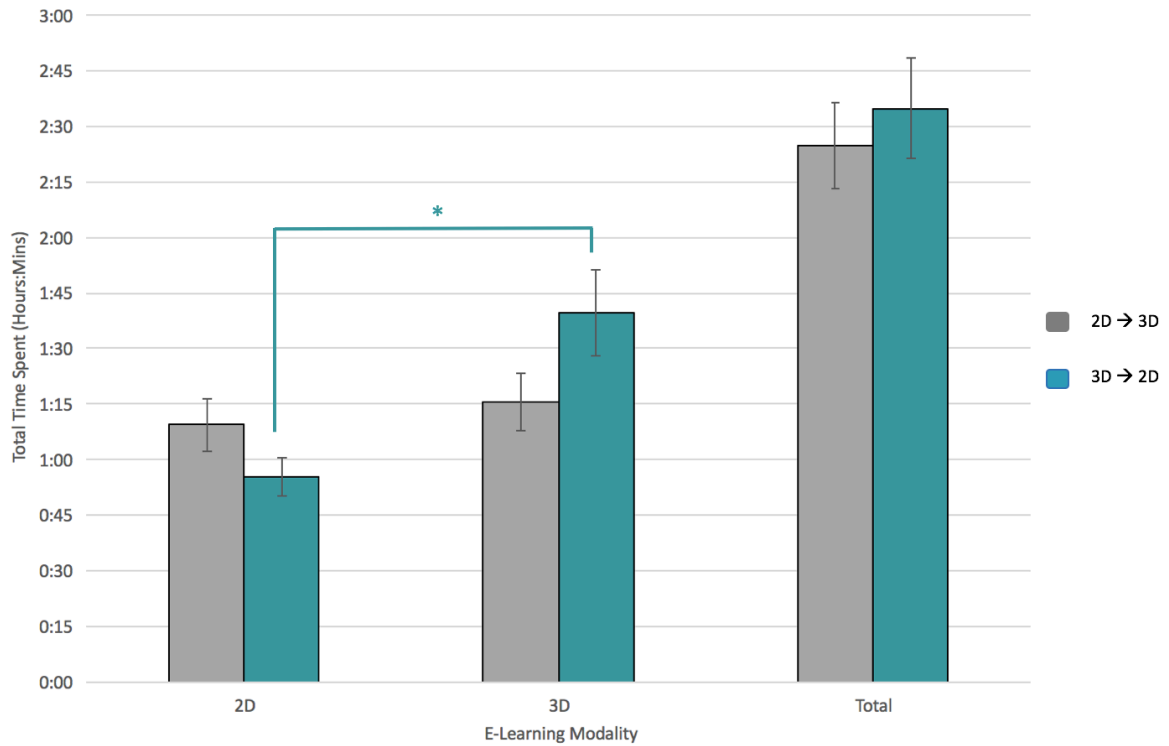
Analysis sought to determine differences in the type, frequency and duration of interactions each participant group made with each of the learning modalities. The data was also collected to determine how participant interactions may have influenced scores on the spatial anatomy knowledge assessments.

Study data were analyzed using R statistical software, version 3.2.2. (R Core Team 2013). The normality of the data was initially assessed using the Shapiro-Wilk test for normality, which revealed a significant departure in the data from normality,  $W=0.969$ ,  $p=0.04$ . As the data significantly deviated from normality, further analysis of the data utilized non-parametric measures.

To examine potential difference in the time spent using each of the e-learning modalities within participant groups, Wilcoxon Signed Rank tests with a continuity correction were performed. No significant differences were observed in the time spent utilizing the 2D and 3D e-learning resources for participants in Group A ( $W=468.5$ ,  $p>0.05$ ). Conversely, participants in Group B spent significantly more time utilizing the 3D resource as compared to the time utilizing the 2D resource ( $W=570.5$ ,  $p<0.001$ ).

Mann-Whitney U tests were calculated on mean time values between participant groups within the same assessment. No significant differences were observed between groups on the length of time for which the 2D or the 3D e-learning resources were accessed respectively ( $U=2255.5$ ,  $p>0.05$ ;  $U=2375$ ,  $p>0.05$ ). Further, no significant differences were observed to the total amount of time spent utilizing both the 2D and 3D e-learning resource. Summary of these results are displayed in Figure 33 and Table 5.



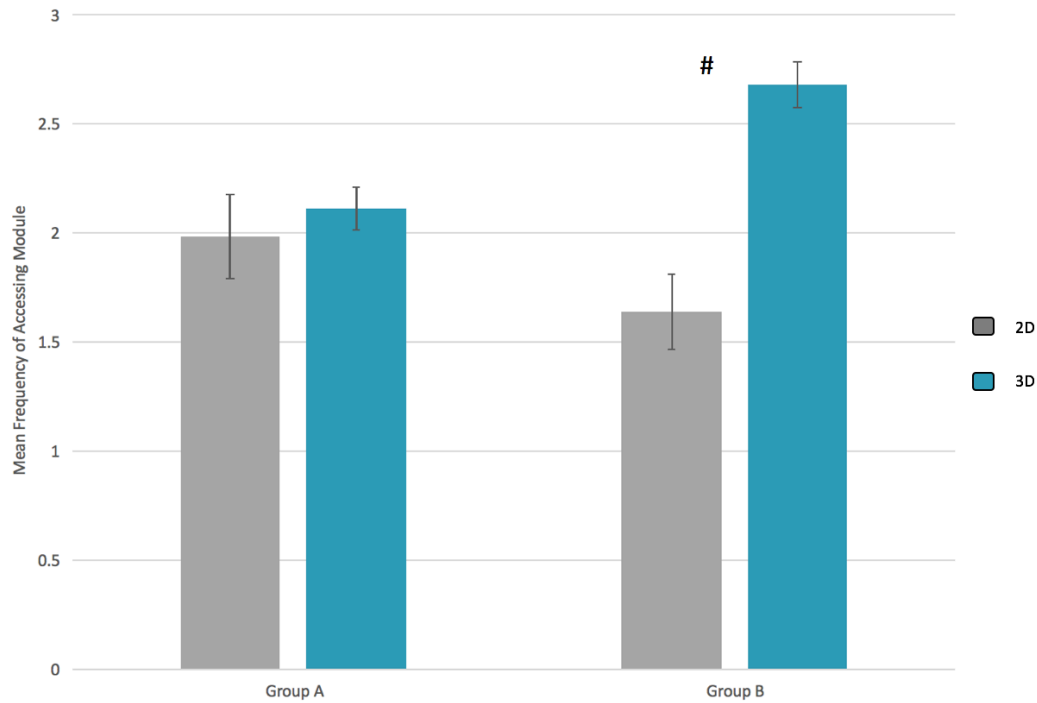


**Figure 33: Mean time of utilizing each of the learning resources (2D e-learning vs 3D e-learning); (Mean  $\pm$  SE; n=169). \* indicates a significant difference within a group in spatial anatomy knowledge assessment scores at  $p<0.001$ . # indicates a significant intragroup difference in the length of time spent utilizing each of the two learning modalities  $p<0.05$ .**

**Table 5: Descriptive statistics of mean time of utilizing each of the learning resources (2D e-learning vs 3D e-learning) within participant groups.**

	Mean (hrs:mins:secs $\pm$ SEM)	Median (hrs:mins:secs)	Q1 (hrs:mins:secs)	Q3 (hrs:mins:secs)
2D Learning Modality				
Group A (2D $\rightarrow$ 3D)	1:09:23 $\pm$ 0:07	0:44:09	0:33:17	1:22:48
Group B (3D $\rightarrow$ 2D)	0:55:16 $\pm$ 0:05	0:40:16	0:32:38	1:15:06
3D Learning Modality				
Group A (2D $\rightarrow$ 3D)	1:15:26 $\pm$ 0:07	0:45:28	0:39:36	1:27:34
Group B (3D $\rightarrow$ 2D)	1:39:30 $\pm$ 0:11	1:12:39	0:38:56	2:00:05
Total				
Group A (2D $\rightarrow$ 3D)	2:24:46 $\pm$ 0:11	1:56:59	1:21:27	2:48:57
Group B (3D $\rightarrow$ 2D)	2:34:46 $\pm$ 0:13	2:05:15	1:19:41	2:58:14

Further analysis sought to determine whether the difference in time spent utilizing the two learning modalities in group B, who initially accessed the 3D e-learning resource, was related to frequency with which the resources were accessed. At no time during the experimental protocol were both learning resources available to participants of either group. As shown in Figure 34, participants in Group B accessed the 3D e-learning resource significantly more frequently, than the 2D e-learning resource during the period of time that each of the learning resources were available ( $W=233.5$   $p<0.001$ ). No significant differences were observed in the frequency with which participants in Group A accessed the 2D resources as compared to the 3D resources ( $W=449$ ,  $p>0.05$ ). A descriptive summary of the data is shown in Table 6.



**Figure 34: Mean frequency of use of each learning modality within participant groups. Participants in Group B accessed the 3D e-learning resource significantly more frequently, than the 2D e-learning resource during the period of time that each of the learning resources were available ( $W=233.5$   $p<0.001$ ). No significant differences were observed in the frequency with which participants in Group A accessed the 2D resources as compared to the 3D resources ( $W=449$ ,  $p>0.05$ ). Participants in Group A initially accessed the 2D e-learning resource, followed by access to the 3D e-learning resource. Participants in Group B viewed the resources in opposite order and initially accessed the 3D e-learning resource, followed by access to the 2D e-learning resource. # indicates a significant difference between groups in spatial anatomy knowledge assessment scores within a single assessment at  $p<0.01$ .**

**Table 6: Descriptive statistics of mean frequency of use of each learning modality within participant groups.**

	Mean ( $\pm$ SEM)	Median	Q1	Q3
2D Learning Modality				
Group A (2D $\rightarrow$ 3D)	2.11 $\pm$ 0.19	2	1	2.25
Group B (3D $\rightarrow$ 2D)	1.99 $\pm$ 0.17	1	1	2
3D Learning Modality				
Group A (2D $\rightarrow$ 3D)	2.68 $\pm$ 0.28	2	1	2
Group B (3D $\rightarrow$ 2D)	1.64 $\pm$ 0.13	2	1	3

### 5.3.1 Evaluation of Interactions with the E-Learning Modalities

Analysis of user data was also completed to determine if individual differences in spatial ability level may influence interaction patterns with the 2D and 3D e-learning resources. Similar to the observations within the undergraduate medicine student and undergraduate allied health sciences student populations. The mean ( $\pm$  SD) Santa Barbara Solids Test score of spatial ability were calculated separately for male and female participants ( $19.69 \pm 6.25$  and  $18.76 \pm 5.47$  respectively). A Mann Whitney U test to evaluate potential sex differences in spatial ability found no significant differences were observed between the two groups ( $W=2711$ ,  $p=0.09$ ), so no further analysis across sexes was performed. so no further analysis across sexes was performed.

The mean ( $\pm$  SD) Mental Rotations Test score of spatial ability were also calculated separately for male and female participants ( $16.40 \pm 3.03$  and  $18.05 \pm 3.51$  respectively). A Mann Whitney U test to evaluate potential sex differences in spatial ability found no significant differences were observed between the two groups ( $W=2744$ ,  $p=0.11$ ), so no further analysis across sexes was performed. so no further analysis across sexes was performed.

Participants within each group were ranked based on their spatial ability, and separated into quartiles. Participants in the first quartile (spatial ability score 4-15) were categorized as having low spatial ability, and participants in the fourth quartile (spatial ability score 25- 27) were considered to have high spatial ability. Results of interactions with the interactive menu, which was identical for both learning modalities, were visualized using matrices that were colour-coded to correspond with frequency of an interaction pair occurring. If an interaction pair occurred at a low frequency, that specific cell in the matrix appeared green in colour. Interaction pairs with relative moderate frequencies appeared yellow in colour, while those with high frequencies appeared red in colour. The full matrices of interactions with the 3D and 2D resources may be viewed in Appendix C and D respectively, however, the greatest variation in interactions with the interactive menu across groups was observed for the subcortical structures. The frequency matrices

for high spatial ability and low spatial ability participants with the interactive menus of the 3D and 2D e-learning resources are displayed in Figure 35 and 36 respectively.

High 3D	Subcortical Menu	White Matter	CorpusCallosum	InternalCapsule	Fornix	CaudatNucleus	GlobusPallidus	Putamen	Thalamus	Hippocampus	Hypothalamus
Subcortical Menu	1	26	9	2	10	7	5	2	7	3	2
White Matter	0	1	30	3	1	2	0	0	0	0	0
CorpusCallosum	2	5	0	48	2	1	2	1	0	0	0
InternalCapsule	0	6	16	0	40	5	3	7	1	0	2
Fornix	0	0	3	15	0	45	3	0	0	2	1
CaudatNucleus	0	1	3	6	12	1	56	1	1	1	1
GlobusPallidus	0	1	1	4	3	23	3	55	6	1	1
Putamen	0	1	3	1	2	6	22	2	43	4	1
Thalamus	0	0	0	1	1	1	5	16	1	34	4
Hippocampus	0	0	1	0	3	1	0	5	5	0	37
Hypothalamus	1	0	2	3	1	1	2	2	6	11	4
A)											
Low 3D	Subcortical Menu	White Matter	CorpusCallosum	InternalCapsule	Fornix	CaudatNucleus	GlobusPallidus	Putamen	Thalamus	Hippocampus	Hypothalamus
Subcortical Menu	9	69	25	10	14	12	11	10	7	1	0
White Matter	0	7	93	6	1	1	1	0	1	0	0
CorpusCallosum	2	20	7	115	6	6	1	1	1	0	2
InternalCapsule	0	9	37	1	102	20	4	8	5	0	0
Fornix	0	2	3	36	0	110	6	1	1	1	0
CaudatNucleus	0	0	6	20	34	4	121	7	4	1	0
GlobusPallidus	0	3	0	3	4	44	7	125	11	2	1
Putamen	0	2	2	4	3	8	54	5	98	8	0
Thalamus	0	1	2	5	0	2	7	26	4	96	9
Hippocampus	1	3	1	0	0	2	1	6	19	4	84
Hypothalamus	3	3	2	2	5	3	3	2	8	22	3
B)											

**Figure 35: Colour-coded frequency matrix of paired-interactions with the interactive user menu with the 3D e-learning resource. Participants were divided into quartiles based on their Santa Barbara Solids Test of spatial ability scores. Low spatial ability participants in quartile one (A) had a Santa Barbara Solids Test score ranging from 4-15, whereas the range of Santa Barbara Solids Test scores for high spatial ability individuals (B) was 25-27. Green indicates low frequency, yellow indicates a moderate frequency, while red identified interactions that occurred with a high frequency.**

High 2D	Subcortical Menu	White Matter	CorpusCallosum	InternalCapsule	Fornix	CaudatNucleus	GlobusPallidus	Putamen	Thalamus	Hippocampus	Hypothalamus
Subcortical Menu	7	0	35	0	4	0	4	3	2	0	3
White Matter	0	0	0	0	0	0	0	0	0	0	0
CorpusCallosum	0	0	1	0	2	0	3	0	1	1	0
InternalCapsule	0	0	0	0	0	0	0	0	0	0	0
Fornix	0	0	2	0	2	0	1	1	0	0	0
CaudatNucleus	0	0	0	0	0	0	0	0	0	0	0
GlobusPallidus	0	0	1	0	2	0	1	44	5	0	1
Putamen	2	0	0	0	0	0	17	0	43	1	1
Thalamus	0	0	1	0	0	0	3	18	1	36	3
Hippocampus	0	0	1	0	2	0	0	0	10	1	37
Hypothalamus	3	0	1	0	2	0	0	3	3	13	0
A)											
Low 2D	Subcortical Menu	White Matter	CorpusCallosum	InternalCapsule	Fornix	CaudatNucleus	GlobusPallidus	Putamen	Thalamus	Hippocampus	Hypothalamus
Subcortical Menu	1	0	45	0	4	0	3	2	3	2	1
White Matter	0	0	0	0	0	0	0	0	0	0	0
CorpusCallosum	1	0	1	0	3	0	0	1	0	0	1
InternalCapsule	0	0	0	0	0	0	0	0	0	0	0
Fornix	0	0	3	0	0	0	4	1	1	0	0
CaudatNucleus	0	0	0	0	0	0	0	0	0	0	0
GlobusPallidus	0	0	2	0	2	0	1	74	5	0	0
Putamen	0	0	0	0	1	0	23	0	62	4	2
Thalamus	0	0	0	0	0	0	6	23	1	53	3
Hippocampus	0	0	0	0	1	0	0	3	17	2	49
Hypothalamus	1	0	6	0	0	0	1	3	2	18	0
B)											

**Figure 36: Colour-coded frequency matrix of paired-interactions with the interactive user menu with the 2D e-learning resource. Participants were divided into quartiles based on their Santa Barbara Solids Test of spatial ability scores. Low spatial ability participants in quartile one (A) had a Santa Barbara Solids Test score ranging from 4-15, whereas the range of Santa Barbara Solids Test scores for high spatial ability individuals (B) was 25-27. Green indicates low frequency, yellow indicates a moderate frequency, while red identified interactions that occurred with a high frequency.**



The raw and normalized frequencies of interaction pairs in the subcortical section of the e-learning resource interface menus are shown in Table 7. No significant differences were observed between the raw frequencies of paired interaction for participants of high and low spatial ability when using the 2D e-learning resource ( $W=42$ ,  $P>0.05$ ). When the interactions with the 3D e-learning interface menu were examined, low spatial individuals had a significantly higher number of interactions with the user interface as compared to participants with high spatial ability ( $W=0$ ,  $p<0.01$ ). Wilcoxon Signed Ranks tests of paired differences also reveal significantly higher frequencies of interactions for high and low spatial ability users respectively with the 3D resource as compared to the 2D resource ( $W=1$ ,  $p<0.05$ ;  $W=0$ ,  $p<0.05$ ).

**Table 7: Raw Frequency Data for Paired Interactions within the Subcortical Structure portion of the menu presented in the e-learning resource interface**

	High Spatial Ability 2D	Low Spatial Ability 2D	High Spatial Ability 3D	Low Spatial Ability 3D
Subcortical Menu& White Matter	0	0	26	69
White Matter& Corpus Callosum	0	0	30	93
Corpus Callosum& Internal Capsule	0	0	48	115
Internal Capsule & Fornix	0	0	40	102
Fornix& Caudate Nucleus	0	0	45	110
Caudate Nucleus& Globus Pallidus	0	0	56	121
Globus Pallidus& Putamen	44	74	55	125
Putamen& Thalamus	43	62	43	98
Thalamus& Hippocampus	36	53	34	96
Hippocampus& Hypothalamus	37	49	37	84

No significant differences were observed in the normalized frequencies of paired interactions with the user interface menu between high and low spatial ability participants when using either the 2D or 3D e-learning resource respectively ( $W=57$ ,  $P>0.05$ ;  $W=53$ ,  $p>0.05$ ) as displayed in Table 8.

**Table 8: Normalized Frequency Data for Paired Interactions within the Subcortical Structure portion of the menu presented in the e-learning resource interface**

	High Spatial Ability 2D	Low Spatial Ability 2D	High Spatial Ability 3D	Low Spatial Ability 3D
Subcortical Menu& White Matter	0	0	6.28%	6.81%
White Matter& Corpus Callosum	0	0	7.25%	9.18%
Corpus Callosum& Internal Capsule	0	0	11.59%	11.35%
Internal Capsule & Fornix	0	0	9.66%	10.07%
Fornix& Caudate Nucleus	0	0	10.87%	10.86%
Caudate Nucleus& Globus Pallidus	0	0	13.52%	11.94%
Globus Pallidus& Putamen	27.50%	31.09%	13.29%	12.34%
Putamen& Thalamus	26.88%	26.05%	10.38%	9.67%
Thalamus& Hippocampus	22.50%	22.27%	8.21%	9.48%
Hippocampus& Hypothalamus	23.12%	20.59%	8.94%	8.29%

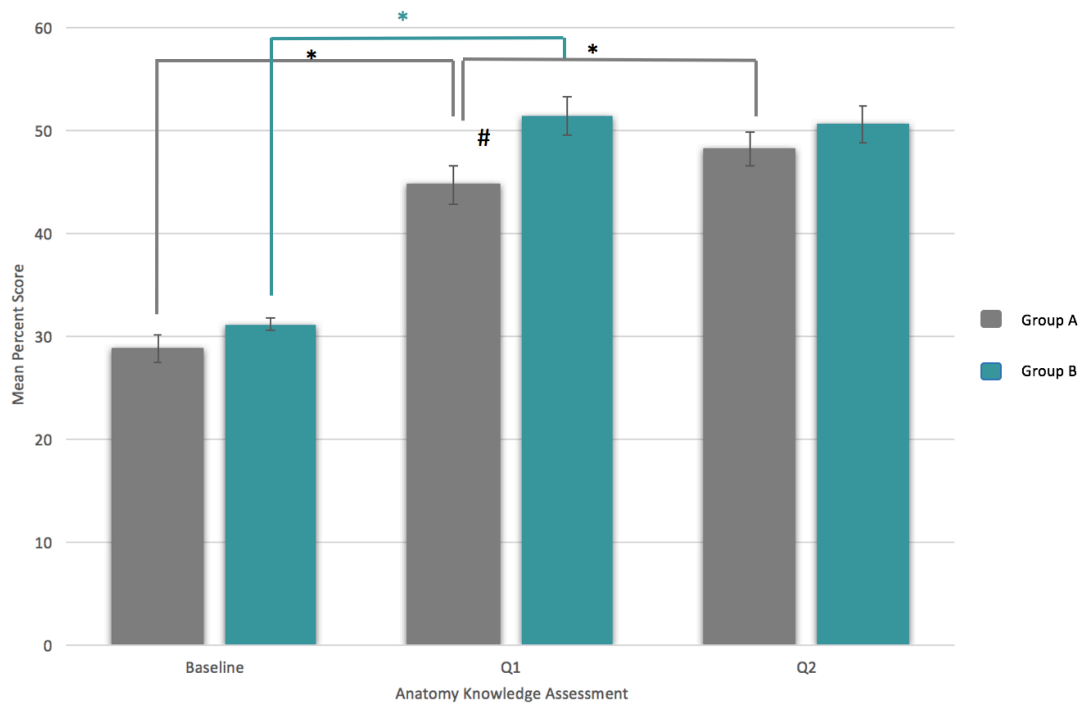
### 5.3.2 Evaluation of Learning Outcomes Across Learning Modalities

To examine potential differences within participant groups on the written assessments of anatomy knowledge assessments, Wilcoxon Signed Rank tests with a continuity correction were performed. A summary of descriptive statistics is shown in Table 9. Participants in both Group A and Group B significantly improved their performance between the baseline and quiz #1 knowledge assessments respectively ( $W=2035$ ,  $p<0.01$ ;  $W=6$ ,  $p<0.01$ ). Additionally, participants in Group A who accessed the 3D e-learning resource following exposure to the 2D e-learning resource, significantly improved their mean percent performance on quiz #2 as compared to the performance on quiz #1 ( $W=1390.5$ ,  $p=0.01$ ), however, a significant result was not observed for participants in Group B who accessed the 2D e-learning resources following exposure to the 3D e-learning resource.

Mann-Whitney U tests assessed differences in mean percent scores between participant groups within the same assessment. No significant differences were observed between groups on the baseline knowledge assessment or spatial ability scores. Analysis between groups did reveal a significant difference between mean percent scores on quiz #1. Participants who initially accessed the 3D e-learning resource performed significantly better than participants who were provided initial access to the 2D e-learning resources, ( $U=2888$ ,  $p=0.02$ ). There were no significant differences observed between groups on quiz #2, after participants had accessed both learning resource modalities. Further, no significant differences were observed in performance between question categories across assessments or between learning modalities. Mean percent performance across spatial anatomy knowledge assessments is displayed in Figure 37.

Results of the relationships between performance on the anatomy knowledge assessment and scores of spatial ability did not significantly differ from the observations of previous studies conducted. A significant positive relationship was observed between participants' scores of spatial ability as measured by the Santa Barbara Solids Test and performance on baseline, quiz #1, and quiz #2 spatial anatomy knowledge assessments respectively ( $r_s=0.16$ ,  $p<0.05$ ;  $r_s=0.22$ ,  $p<0.05$ ;  $r_s=0.51$ ,  $p<0.01$ ). Positive correlations were also

observed between participants' scores of spatial ability as measured by the Mental Rotations Test on the baseline, quiz #1, and quiz #2 spatial anatomy knowledge assessments respectively ( $r_s=0.14$ ,  $p<0.05$ ;  $r_s=0.20$ ,  $p<0.05$ ;  $r_s=0.41$ ,  $p<0.01$ ) No significant differences were observed in the spatial ability correlations of scores on the SBST or the MRT with the scores on the spatial anatomy knowledge assessments.



**Figure 37: Mean percent score across spatial anatomy knowledge assessments subsequent to access to e-learning resource modalities (2D e-learning vs 3D e-learning); (Mean  $\pm$  SEM;  $n=169$ ). \* indicates a significant difference within groups across assessment scores at  $p<0.01$ . # indicates a significant difference between groups in assessment scores within a single assessment at  $p<0.05$ .**

**Table 9: Descriptive statistics across spatial anatomy knowledge assessments subsequent to access to e-learning resource modalities**

	Mean (% $\pm$ SEM)	Median (%)	Q1 (%)	Q3(%)
Baseline Spatial Anatomy Knowledge Assessment				
Group A (2D $\rightarrow$ 3D)	28.57 $\pm$ 1.41	27.03	18.92	37.84
Group B (3D $\rightarrow$ 2D)	31.11 $\pm$ 1.55	29.73	24.32	40.54
Spatial Anatomy Post-Knowledge Assessment #1				
Group A (2D $\rightarrow$ 3D)	44.52 $\pm$ 1.86	45.95	29.73	56.76
Group B (3D $\rightarrow$ 2D)	51.32 $\pm$ 1.87	50.00	37.84	64.86
Spatial Anatomy Post-Knowledge Assessment #2				
Group A (2D $\rightarrow$ 3D)	48.11 $\pm$ 1.66	48.48	36.36	57.58
Group B (3D $\rightarrow$ 2D)	50.61 $\pm$ 1.80	51.52	36.36	63.64

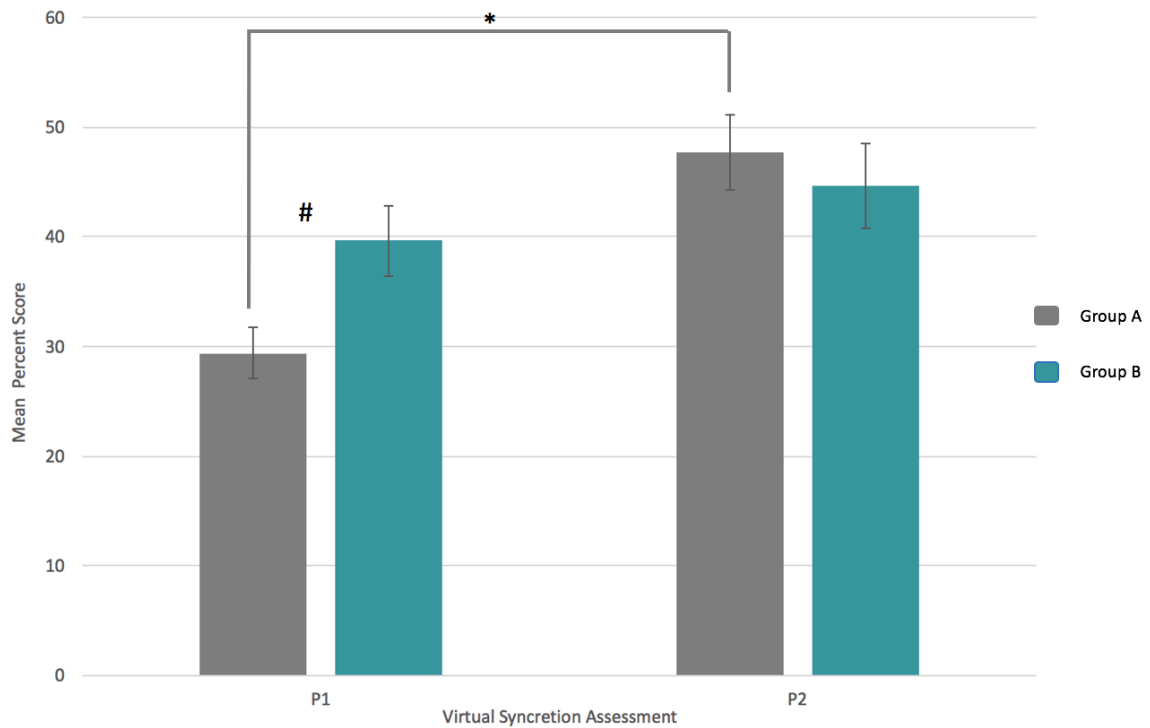
To examine potential difference within participant groups on the question-directed virtual syncretion assessments of spatial anatomy knowledge, Wilcoxon Signed Rank tests with a continuity correction were performed. Participants in Group A, who initially accessed the 2D e-learning resources followed by 3D resources, significantly improved their performance across the virtual syncretion assessments ( $W=471.5$ ,  $p<0.01$ ). In contrast, participants in Group B who accessed the 3D resources initially, and 2D resources subsequently, did not improve their performance between virtual syncretion assessments ( $W=726$ ,  $p>0.05$ ).

Mann-Whitney U tests were also performed to evaluate differences of mean percent assessment scores between participant groups within the same assessment. Participants who initially accessed the 3D e-learning resource performed significantly better on the first virtual syncretion assessment as compared to participants initially provided access to the 2D e-learning resources, ( $U=2939$ ,  $p=0.047$ ). There were no significant differences observed between groups on virtual syncretion assessment #2, after all participants had accessed both learning resource modalities. Mean percent performance across virtual syncretion assessments is displayed in Figure 38.

A significant positive relationship was observed between participants' scores of spatial ability as measured by the Santa Barbara Solids Test and performance on first and second virtual syncretion assessments respectively ( $r_s=0.236$ ,  $p<0.05$ ;  $r_s=0.26$ ,  $p<0.05$ ). Positive correlations were also observed between participants' scores of spatial ability as measured by the Mental Rotations Test on the baseline, quiz #1, and quiz #2 spatial anatomy knowledge assessments respectively ( $r_s=0.18$ ,  $p<0.05$ ;  $r_s=0.26$ ,  $p<0.05$ ;) No significant differences were observed in the spatial ability correlations of scores on the SBST or the MRT with the scores on the virtual syncretion assessments.

Results of the relationships between performance on the virtual syncretion assessment and scores of spatial ability as measured by the MRT revealed a significant positive relationship between participants' scores of spatial ability and improvement in performance across virtual syncretion assessments for participants in group B, who

initially access the 3D resource, followed by the 2D resource ( $r_s = 0.26$ ,  $p < 0.05$ ). In contrast, no significant relationship between participants' scores of spatial ability and improvement in performance across virtual syncretion assessments for participants in group A, who initially access the 2D resource, followed by the 3D resource ( $r_s = -0.02$ ,  $p > 0.05$ ). Descriptive statistics across groups are presented for each of the virtual puzzle assessments in Table 10.



**Figure 38: Mean percent score across virtual syncretion assessments following access to the e-learning resource modalities (2D e-learning vs 3D e-learning); (Mean  $\pm$  SEM;  $n=169$ ). \* indicates a significant difference within a group in virtual syncretion assessment scores at  $p < 0.05$ . # indicates a significant difference between groups in spatial anatomy knowledge assessment scores within a single assessment at  $p < 0.05$ .**

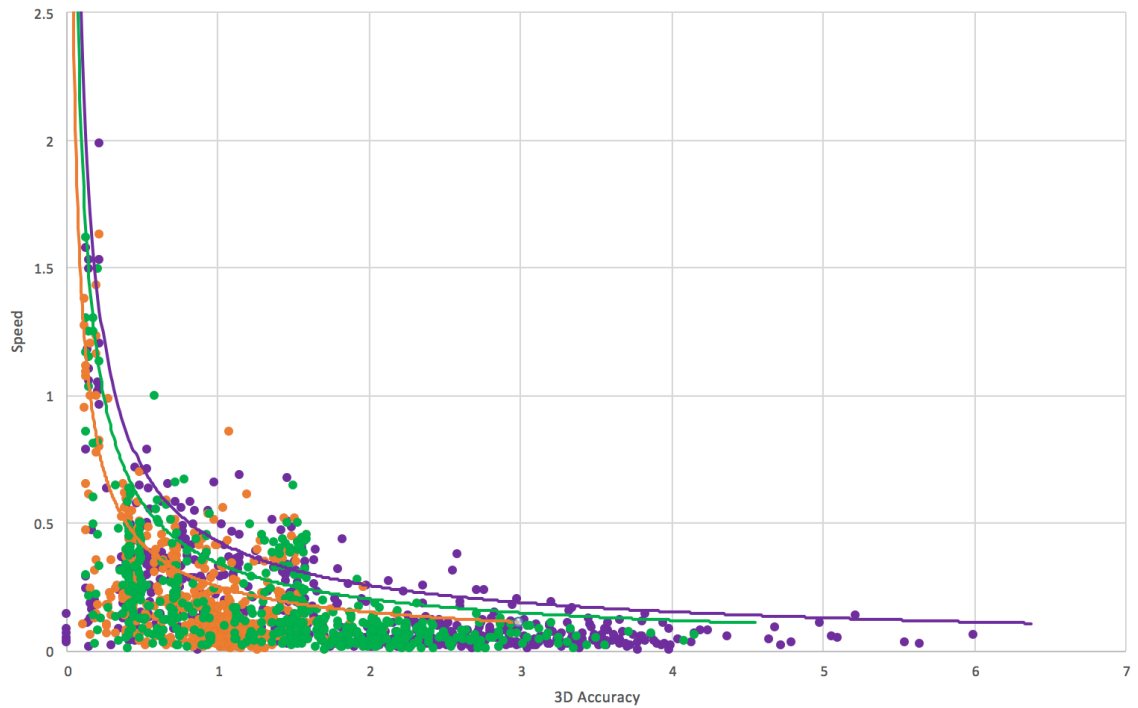
**Table 10: Descriptive Statistics across virtual syncretion assessments following access to the e-learning resource modalities.**

	Mean (% $\pm$ SEM)	Median (%)	Q1 (%)	Q3(%)
Virtual Puzzle Assessment #1				
Group A (2D $\rightarrow$ 3D)	29.01 $\pm$ 2.35	28.57	14.29	42.86
Group B (3D $\rightarrow$ 2D)	39.60 $\pm$ 3.16	28.57	14.29	57.14
Virtual Puzzle Assessment #2				
Group A (2D $\rightarrow$ 3D)	48.70 $\pm$ 3.42	42.86	28.57	85.71
Group B (3D $\rightarrow$ 2D)	44.67 $\pm$ 3.86	28.57	14.29	71.42



### 5.3.3 Accuracy of Performance in Virtual Syncretion Assessments

The accuracies of the placement of each anatomical structure within the tasks of the virtual syncretion assessment were also assessed using the data collected for each session initiated by the participants. The data collected included the position along the x, y, and z axes and the time elapsed between selection and placement of each structure. The recorded positional values were compared to the expected values of the structures, which were determined based on each structure's position within the fully assembled 3D model. The differences between these actual and values represent the amount of error incurred by the participant during the placement of each structure. The distance error was calculated as the square root of the sum of the squares of the differences between the expected and actual coordinates within the 3D environment. As outlined by Fitts' Law, the performance on a task was a trade-off between accuracy and speed, such that as speed increases, accuracy decreases, and vice-versa. Accuracy was computed as a logarithmic function of the reciprocal of 3D error value, whereas the speed was the reciprocal value of the placement time. The closer the values of performance values were to zero, the lower the performance, which may be approximated using a hyperbolic curve. Conversely, higher performance was delineated by higher levels of accuracy in shorter durations of time, resulting in a hyperbolic curve that appeared higher above the horizontal axis. User performance during a representative task within the virtual syncretion assessment for three neuroanatomical structures (corpus callosum, fornix, and globus pallidus) are presented in Figure 39. Of the structures presented, users' performance was highest for the placement of the corpus callosum, as shown by the distribution of data higher above the horizontal axis. The lowest performance was observed in the placement of the globus pallidus, as shown by the distribution of the data closer to the horizontal axis. Each curve represents the performance level which was only exceed in 5% of tasks recorded.



**Figure 39: Combined performance assessment using Fitts' Law methodology on a representative virtual syncretion task. The placement data for the corpus callosum is shown in purple, while the data for the placement of the fornix is shown in green, and the globus pallidus in orange. Of the structures presented, user performance was highest for the placement of the corpus callosum, as shown by the distribution of data higher above the horizontal axis. The lowest performance was observed in the placement of the globus pallidus, as shown by the distribution of the data closer to the horizontal axis.**

## 5.4 Discussion

Past studies have provided evidence to support the positive impact of high spatial ability on performance in anatomy, particularly on spatially-demanding tasks (Fernandez, Dror, and Smith 2011; Lufler et al. 2012; Langlois et al. 2017). What have yet to be well-established are the differences in underlying cognitive processes and strategies that may be used by novice learners of varying spatial abilities, that contribute to the observed differences in performance. Results from this study have provided evidence that when evaluating the difference e-learning resources developed, participants who initially utilized the 3D e-learning resources accessed the learning materials significantly more frequently, and for longer durations than participants who initially viewed the 2D e-learning resources. While the additional duration of time may be partially attributed to the increased cognitive requirement to learn how to use the features of the 3D e-learning resource, this did not negatively impact learning as participants who initially accessed the 3D e-learning resource performed significantly better on the first post-resource assessment than those who initially accessed the 2D e-learning resource. These results suggest that students were more engaged with 3D e-learning resources, which provides additional support to previous findings that report students demonstrated higher interest to explore 3D models and spent more time interaction with these models as compared to 2D learning resources (Battulga et al. 2012; Foo et al. 2013).

As few studies have evaluated differences in learning strategies employed by students of high and low spatial ability, a second aim of this study was to examine the interaction data recorded by participants while using each learning modality to elucidate any potential patterns that may be observed between groups. User data revealed a significantly higher number of interactions with the user interface for the 3D resource, as compared to the 2D resource with the same menu. Additionally, when assessing interactions with the 3D resource, low spatial ability participants interacted significantly more frequently with the subcortical structures portion of the interactive menu than participants with high spatial ability. However, when the interaction data was normalized, there were no significant differences between high and low spatial ability participants in the proportions of interactions made with each pair of subcortical structures. This result

suggests that while learners with low spatial ability viewed the information more frequently than those with high spatial ability, the type of information being viewed did not differ between the groups. This supports a previous finding that reported high spatial ability users spent less time and performed better on spatial anatomy assessments, however, the strategies utilized by participants with high and low spatial abilities did not significantly differ (Nguyen et al. 2014).

Similar to the results previously observed with the spatial anatomy knowledge assessment, the performance on the virtual syncretion assessment was found to be positively correlated with spatial ability scores. When the change in performance was compared between participant groups across virtual syncretion assessments, it was revealed that change in score only positively correlated to spatial ability score for Group B, who accessed the 2D e-learning resource between the two syncretion assessments. No significant correlations were observed for participants in Group A, who utilized the 3D e-learning resource between the virtual syncretion assessments. This suggests that additional learning of spatial anatomy related to the performance on the final syncretion assessment was independent of spatial ability only when learning from the 3D e-learning resource. This finding aligns with a previous study that showed low spatial ability users demonstrated poor learning outcomes when using static pictures as compared to individuals with high spatial ability, however when learning from dynamic images portraying the same information, learning outcomes were independent of spatial ability (Höffler and Leutner 2011). This may be partially explained by the Ability-as Compensator effect, which proposes that low spatial ability learners are better supported by dynamic images and animations because such resources assist in their building of adequate mental representations (Mayer, Heiser, and Lonn 2001). Since the construction of mental representations from static pictures requires a greater amount of spatial cognitive resources than dynamic models (Mayer 2005), the interactive neuroanatomy model may have provided multiple perspectives, to compensate for a lack of internal visualization ability. This in turn could have facilitated improved knowledge of spatial relationships and enabled improved performance on both the written knowledge assessment and virtual syncretion task for low spatial ability learners.

### 5.4.1 Study Limitations

This study begins to examine the user metrics and interaction patterns with the user interfaces of interactive 2D and 3D e-learning resources, however, a limitation encountered was the restriction of evaluating paired-interactions as compared to longer sequences of interactions within the model. Due to the learner-centered design of the e-learning resources and the resulting high level of variability that was observed in the interactions, it was only possible to perform analysis on pairs of structures that were accessed in direct succession. Future studies would be beneficial to evaluate more extensive sequences of interactions between different groups of participants. It would also be beneficial to examine the paired-interaction frequencies between groups who initially used the 3D e-learning resource, as compared to the participant who used the 3D e-learning module subsequent to interacting with the 2D e-learning resource, to determine if exposure to the convention resources may impact the manner by which students interact with the 3D e-learning resource.

It may also be beneficial to incorporate a subjective questionnaire to provide insight into the participants perceived strategies selected while completing the task. Another limitation to the current study was that spatial ability scores as measured by the MRT or SBST were not correlated to the interaction patterns with the 2D and 3D e-learning resources. If a systematic method could be developed to quantify the types of interactions participants perform while completing the learning objectives, such as frequency and degree of rotation of the 3D model, or categorizing the structures selected, it would help to further elucidate how spatial ability may influence behaviour while learning spatial information.

## 5.5 Conclusions

The present study revealed differences in the frequency and duration of time for which 2D and 3D e-learning resources were utilized by novice students while learning spatial neuroanatomy information. It also revealed that 3D e-learning resources may be more beneficial, particularly for low spatial ability students for improving their performance on a novel virtual syncretion task assessing their level of knowledge of spatial relationships

between neuroanatomy structures. Examination of interaction data with the learning resources revealed that it does not appear that different strategies for learning the spatial information are selected due to level of spatial ability, but rather high spatial ability participants may be able to acquire this information more efficiently, thus requiring fewer interactions with the 3D resource to form an adequate mental representation of the spatial information.

Considering the significance of spatial ability in learning and understanding spatial anatomy information, further work is needed to determine the extent to which its impact on student learning may be modulated. Evidence suggests that spatial ability may be amendable (Carlisle, Tyson, and Nieswandt 2015; Titus and Horsman 2009; Uttal et al. 2013), and particularly in anatomy there may be a reciprocal advantage that exists between experience learning complex anatomical material and improvements in spatial abilities over time (Guillot et al. 2007; Vorstenbosch et al. 2013a). With the evidence provided in this study that 3D resources may be especially beneficial for low spatial ability participants, not only to factual spatial knowledge, but also on performance of a spatial anatomy syncretion task, intervention with spatial ability training exercises or dynamic 3D resources could provide the necessary supplemental support for this student sub-population to improve their spatial ability, and also provide them with the best opportunity of developing a solid foundation of spatial anatomy knowledge to apply in their future studies and career choices.

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## Chapter 6

### 6 Discussion and Conclusions

#### 6.1 Discussion of Principal Results

Education in the anatomical sciences continues to experience many transformations with the ongoing curricular reform and an increase in the educational technologies that are shaping the modernization of pedagogical approaches utilized by educators (Drake et al. 2009; Drake, McBride, and Pawlina 2014; McBride and Drake 2018; Trelease 2016). There continues to be a rising demand for the implementation of e-learning resources across the STEMM disciplines, and specifically in the anatomical sciences, which provide greater flexibility and accessibility, and a reduction in costs incurred from the acquisition and preservation of conventional cadaveric and physical resources (Bailey 2015; McAleese et al. 2013). As new educational technologies and opportunities continue to emerge, it is essential to collect empirical evidence to support their implementation into modernizing curricula, that seek to provide an improved educational experience that meets the learning requirements of an increasingly diverse student population. Chapter 2 sought to develop an interactive e-learning resource that was guided by principles of the Cognitive Load Theory in an effort to reduce the extraneous cognitive load imposed by the learning resource on novice students. As the content and presentation of the e-learning resource could be strictly controlled, this created the possibility to tailor the design of this resource to ensure it was suitable for integration and testing within the curricula of multiple student populations.

While there has been a diverse library of anatomical e-learning tools developed, the evaluations of some tools have relied strictly on qualitative assessments, primarily consisting of student satisfaction as a measure of success (Guy et al. 2015; Silén et al. 2008; Tam et al. 2013). The evaluation of other resources has been more extensive and has examined the impact of such educational technologies on student learning outcomes in areas of anatomy such as the oculomotor system (Glittenberg and Binder 2006), the vascular system (Cui et al. 2017; Petersson et al. 2009), and neuroanatomy (Chariker,

Pani, and Naaz 2011; Drapkin et al. 2015; Estevez, Lindgren, and Bergethon 2010). Chapter 3 sought to empirically evaluate the impact of the integration of the 3D e-learning resource into two distinct student populations, an undergraduate medicine neuroanatomy laboratory course, as well as an undergraduate systemic human anatomy course. The evaluation of the resource required participants to complete tests of spatial ability and baseline knowledge prior to beginning the randomized cross-over design which saw groups utilizing the 3D and conventional resources in reverse order to complete the neuroanatomy learning objectives. During evaluation of the 3D resource, it was observed that students who initially accessed the 3D resource performed significantly better on the post-assessment of spatial neuroanatomy knowledge, as compared to students who initially accessed the conventional 2D e-learning resources. This observation was consistent whether the modality of the conventional resource was cadaveric laboratory specimens in the undergraduate medicine program or 2D images with associated text in an undergraduate systemic human anatomy course. Further, this beneficial impact on learning was observed both when students utilized the resource prior to and following access to conventional learning resources. These results provide further support to the beneficial impact of 3D educational technologies on student learning in neuroanatomy (Drapkin et al. 2015; Estevez, Lindgren, and Bergethon 2010; Pani, Chariker, and Naaz 2013; Ruisoto Palomera, Juanes Méndez, and Prats Galino 2014b).

The significant improvements in performance on a spatial neuroanatomy knowledge assessment in this study, subsequent to interacting with 3D e-learning resource, provide further evidence that 3D visualizations may facilitate participants' ability to identify and locate neuroanatomy structures. This may be due to an improved ability of the participants to create accurate and complete mental representation of the brain structures and their spatial relationships. Educational theories suggest such improvements could be attributed to the 3D learning resources serving as a scaffold to assist in the development of mental representation, and consequently reduce the level of cognitive load experienced by novice students while learning spatial neuroanatomy as compared to conventional, 2D learning resources (Mayer 2005).

The effectiveness of cognitive processing of complex spatial information is largely influenced by an individual's level of spatial ability. Spatial ability has received considerable attention in education psychology research, especially in anatomical and medical education, due to the evidence provided by several studies that have identified a relationship between spatial ability level and both clinical skills acquisition (Abe et al. 2017; Brandt and Davies 2006; Shafqat et al. 2015; Smith et al. 2012) and anatomy knowledge acquisition (Lufler et al. 2012; Nguyen, Nelson, and Wilson 2012). With the increased integration of 3D e-learning visualizations, it is of growing importance to gain a better understanding of the potential impact of 3D visualizations on modulating the necessity of high spatial ability levels for the successful development of spatial anatomy knowledge, and thus minimize the effect of individual differences in spatial ability on determining student success. The aim of Chapter 4 was to differentiate how intrinsic differences in students' spatial ability may influence their success in acquiring spatial anatomy knowledge, and their subsequent performance on the knowledge assessments following their use of both conventional 2D and 3D resources. Additionally, this study sought to determine if learning of the spatial neuroanatomy with 3D resources could occur independently of students' spatial ability.

The results of this study reveal positive correlations observed between participants' spatial ability scores and their performance on a multiple-choice assessment of spatial neuroanatomy knowledge. When possible associations between spatial ability and changes in anatomy assessment scores were investigated for participants who utilized conventional learning resources, significant positive correlations were observed for both the medicine and undergraduate student populations. Further, when the percent change in score was correlated with students' spatial ability for participants provided initial access to the 3D e-learning resource, there was a significant negative correlation observed between spatial ability and change in assessment score for students in the undergraduate medical program. A negative trend was also observed in the relationship between spatial ability and change in anatomy assessment score for students in the undergraduate health science student population. These results suggest that learning outcomes of low spatial ability students improved more from the interactions with the 3D resources and provide additional support to past studies that have reported an amplified benefit of 3D

educational technologies on student learning anatomy particularly for students with low spatial ability (Berney et al. 2015; Brewer et al. 2012; Cui et al. 2017; Luursema et al. 2006).

Such findings suggest that when provided with the correct resources to effectively support learning, the difficulty imposed by low spatial ability on spatial knowledge acquisition can be mitigated, allowing for the successful development of mental representations of complex information such as neuroanatomical structures. Further, these results imply that although individuals with low spatial ability often experience difficulty in forming mental representations, once these representations have been developed, they possess the ability to mentally transform and manipulate these representations. In the final spatial neuroanatomy assessment (Quiz #2), students who interacted with the 3D e-learning resource improved their performance to a level that did not statistically differ from students who initially accessed the 3D e-learning resource, with low spatial ability individuals specifically improving their assessment performance to a level equivalent to their high spatial ability peers. While measures of spatial ability may help predict students' success in learning anatomy and other spatially-complex disciplines, these same measures could alternatively be used to identify those students who may benefit most from the integration of additional visualizations such as 3D e-learning supports, and increase their probability of successfully acquiring spatial anatomy knowledge (Lufler et al. 2012; Cui et al. 2017) or clinical skills (Keri et al. 2015; Langlois et al. 2015; Shafqat et al. 2015).

Successful performance in both anatomy courses, and clinical procedures have been shown to be positively related to students' spatial ability. There is also growing evidence of a reciprocal relationship between the two factors, that reveals experience in spatially-complex subjects is linked to improvements in individuals' spatial ability. However, it is less understood how differences in spatial ability may be underpinning differences in behaviours and strategies utilized by individuals of high and low spatial ability, which contribute to the performance differences observed between these two groups. Chapter 5 sought to evaluate the differences in the interactions with the conventional and 3D e-learning resources, as well as determine how these learning modalities may impact

student performance on a novel virtual syncretion assessment of their spatial neuroanatomy knowledge. This assessment was developed to determine how student learning outcomes may differ when the evaluation format is congruent with the knowledge being assessed rather than providing a nominal response.

User data revealed a significantly greater number of interactions with the user interface for the 3D resource, as compared to the 2D resource with the same menu for all users, independent of their level of spatial ability. Additionally, when assessing interactions with the 3D resource, low spatial ability participants interacted significantly more with the subcortical structures portion of the interactive menu than participants with high spatial ability. However, when the interaction data was normalized, there were no significant differences between high and low spatial ability participants in the proportions of interactions made with each pair of subcortical structures. This result suggests that while learners with low spatial ability viewed the information more frequently than those with high spatial ability, the type of information being viewed did not differ between the groups. This supports a previous finding of strategy selection while completing a spatial anatomy assessment that found high spatial ability user spent less time and performed better on such assessments, however, the strategies utilized by participants with high and low spatial did not significantly differ (Nguyen et al. 2014).

Similar to the results previously observed in the evaluation of this 3D e-learning resource, the performance on the virtual syncretion assessment positively correlated with spatial ability scores as measured by the Santa Barbara Solids Test and Mental Rotation Test. When the change in performance was compared between participant groups across virtual syncretion assessments, it was revealed that change in score only positively correlated to spatial ability score for Group B, who accessed the 2D e-learning resource between the two syncretion assessments. No significant correlations were observed for participants in Group A, who utilized the 3D e-learning resource between the virtual syncretion assessments. This suggests that further learning of spatial anatomy related to the performance on the final syncretion assessment was independent of spatial ability when learning from the 3D e-learning resource. This finding aligns with a previous study that showed low spatial ability users demonstrated poor learning outcomes when using static

pictures as compared to individuals with high spatial ability, however when learning from dynamic images portraying the same information, learning outcomes were independent of spatial ability (Höffler and Leutner 2011).

The results of the studies conducted to evaluate this 3D e-learning resource have demonstrated 3D, dynamic resources may be particularly beneficial for low spatial ability students. Improvements in performance have been observed across both text-based assessments of spatial anatomy knowledge as well as a novel virtual syncretion task. Examination of user data with both 3D and conventional 2D e-learning modalities revealed no significant differences are seen in the learning strategies selected while acquiring spatial information across groups of varying spatial ability, but rather high spatial ability participants may be able to acquire this information more efficiently, thus requiring fewer interactions with the 3D resource to form an adequate mental representation of the spatial information. These findings are directly applicable to anatomy education, as many assessments are performed in time-limited, “bell-ringer” settings. As such it is important for educators to consider how students’ level of spatial ability may affect their ability to understand and interpret spatial anatomy information under time pressures. In such situation students may not be permitted sufficient time or interactions to adequately process, develop, and communicate their understanding of complex spatial information.

## 6.2 Limitations

Due to the limited nature of the neuroanatomy curricula in both student populations, the evaluation of 3D e-learning resource concentrated on evaluating the short-term impact of the resource on student learning outcomes. The evaluation of the effect of the 3D resource on students’ long-term retention of a spatial neuroanatomy knowledge was not possible due to the low number of both course hours and questions dedicated to spatial neuroanatomy concepts included within anatomy course examinations. Without data available on students’ long-term knowledge retention of spatial relationships in neuroanatomy when using the 3D resource, it was not possible to draw conclusions at this time involving its long-term impact on the improvement of students’ knowledge of neuroanatomy beyond their basic anatomy education, and the potential role this may play



in the reduction of neurophobia rates reported by novice students and medical graduates entering clinical settings.

Additionally, the Santa Barbara Solids Test was selected as the singular measure of spatial ability for the first two studies evaluating the impact of the 3D e-learning resource student learning outcomes. While the test has been determined to be both a reliable and valid measure of spatial ability (Cohen and Hegarty 2012), there are a variety of other tests of spatial ability that have been used in some of the other studies discussed, with the Mental Rotation Test most frequently selected as the measure of spatial ability in these studies. As a result, further studies are warranted to examine the reliability and validity of the results between the SBST and other tests of spatial ability.

This study also begins to examine the user metrics and interaction patterns with the user interfaces of interactive 2D and 3D e-learning resource, however, due to the learner-centered design of the e-learning resources and the resulting high level of variability that was observed in the interactions, it was only possible to perform analysis on pairs of structures that were accessed in direct succession. Further identification of more extensive interaction pathways with the resource that may be preferential for learning is required to allow for the investigation frequency of occurrence for these patterns across groups of high and low spatial ability learners.

### 6.3 Future Directions

Several questions have arisen from the results of this study, which warrant further investigation in future studies to explore the diverse applications of the 3D e-learning resource into neuroanatomy curricula. While exposure to the 3D e-learning resource was limited to a short duration of time of approximately one week, the positive impact of its integration into both laboratory and didactic course designs warrants further investigation into the potential impact of long-term exposure over the full duration of neuroanatomy course instruction.

The 3D and 2D e-learning resources evaluated utilized a learner-centered approach that promoted active engagement and interactions by the participants. In addition to the

student, the teacher and teaching strategies employed are also significant factors that influence student achievement (Hattie, 2009). Future directions could investigate the potential impact of the integration of the e-learning resources on a primarily teacher-centered learning environment, in which characteristics such as teacher-student relationship, teacher expectations and clarity of teachers' communication during instruction will also influence the learning process (Hattie, 2009). Analysis could be performed to determine how the e-learning resources may impact student knowledge in situations where factors such as teacher-student relationships, or clarity of communication have been identified as obstacles in the learning process.

Further research may also seek to quantify the more extensive interaction patterns that occur with e-learning resources of differing modalities and across student populations of individual differences including spatial ability. If spatial cognitive abilities can be enhanced through the support of 3D learning resources, it is essential to determine what effect such resources may have in modulating the role of spatial ability for low-spatial ability learners to achieve their maximum success in their education and future careers not only in the anatomical sciences but across many spatially-complex STEMM disciplines.

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# Appendices

## Appendix A: Ethics Approval Notice



Western  
Research

Research Ethics

Use of Human Participants - Initial Ethics Approval Notice

Principal Investigator: Dr. Sandrine de Ribaupierre  
File Number: 104670  
Review Level: Delegated  
Protocol Title: A Novel Approach to Teaching Neuroanatomy  
Department & Institution: Schulich School of Medicine and Dentistry/Clinical Neurological Sciences, Western University  
Sponsor:  
Ethics Approval Date: March 20, 2014 Expiry Date: February 28, 2019  
Documents Reviewed & Approved & Documents Received for Information:

Document Name	Comments	Version Date
Instruments	Examples of the anatomy quiz	2013/11/30
Instruments	Examples of Visuo-spatial Tests	2013/11/30
Letter of Information	LOI clean Study A	2014/02/18
Letter of Information	LOI clean Study B	2014/02/18
Response to Board Recommendations	Response	2014/02/20
Instruments	Questionnaire Demographic	2014/02/20
Instruments	Questionnaire usability	2014/02/20
Instruments	Santa Barbara Test	2014/02/20
Instruments	Pre and post test	2014/02/18
Other	Block Diagram Study B	2014/02/20
Other	Block Diagram Study A	2014/02/20
Response to Board Recommendations	Response	2014/03/16
Western University Protocol	PDF clean version	2014/03/16

This is to notify you that The University of Western Ontario Research Ethics Board for Health Sciences Research Involving Human Subjects (HSREB) which is organized and operates according to the Tri-Council Policy Statement: Ethical Conduct of Research Involving Humans and the Health Canada/ICH Good Clinical Practice Practices: Consolidated Guidelines; and the applicable laws and regulations of Ontario has reviewed and granted approval to the above referenced revision(s) or amendment(s) on the approval date noted above. The membership of this REB also complies with the membership requirements for REB's as defined in Division 5 of the Food and Drug Regulations.

The ethics approval for this study shall remain valid until the expiry date noted above assuming timely and acceptable responses to the HSREB's periodic requests for surveillance and monitoring information. If you require an updated approval notice prior to that time you must request it using the University of Western Ontario Updated Approval Request Form.

Members of the HSREB who are named as investigators in research studies; or declare a conflict of interest, do not participate in discussion related to, nor vote on, such studies when they are presented to the HSREB.

The Chair of the HSREB is Dr. Joseph Gilbert. The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

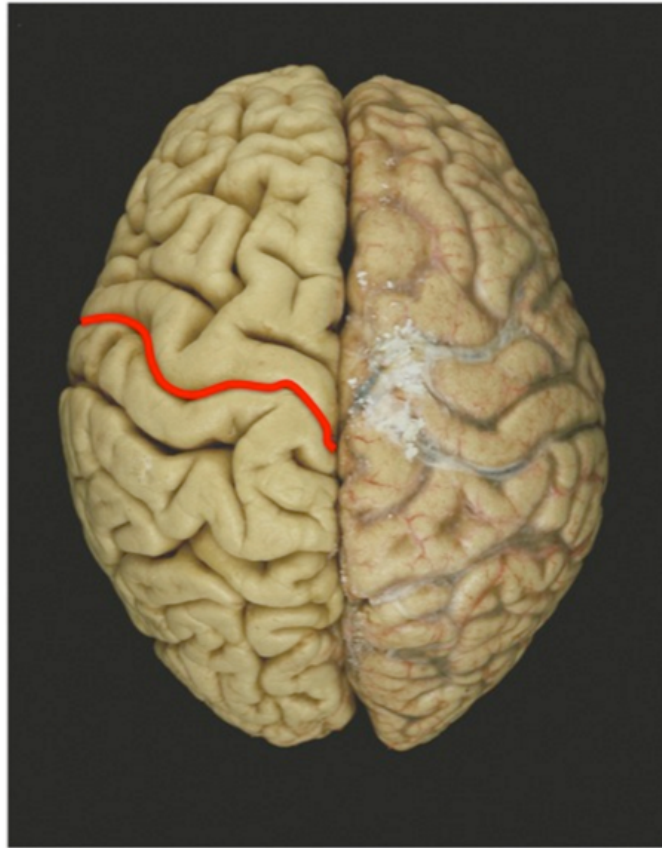
*This is an official document. Please retain the original in your files.*

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London, ON, Canada N6A 3K7 t: 519.661.3036 f: 519.850.2466 [www.uwo.ca/research/services/ethics](http://www.uwo.ca/research/services/ethics)

## Appendix B: Representative Exemplars of Spatial Anatomy Knowledge Assessment Questions

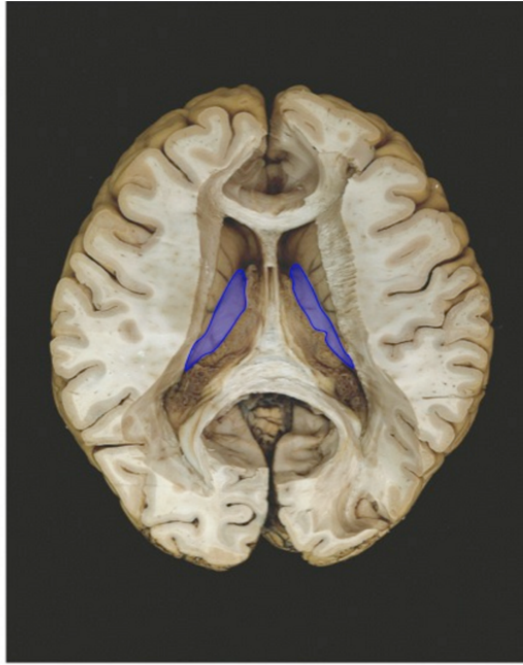
You are walking from the medial longitudinal fissure towards the inferior aspect of the cortex. After you cross Broca's area, you might you fall into the cerebral structure known as the

If you are standing on the surface of the globus pallidus, the structure directly medial to your position is known as the



The structure outlined in red in the image above is the .

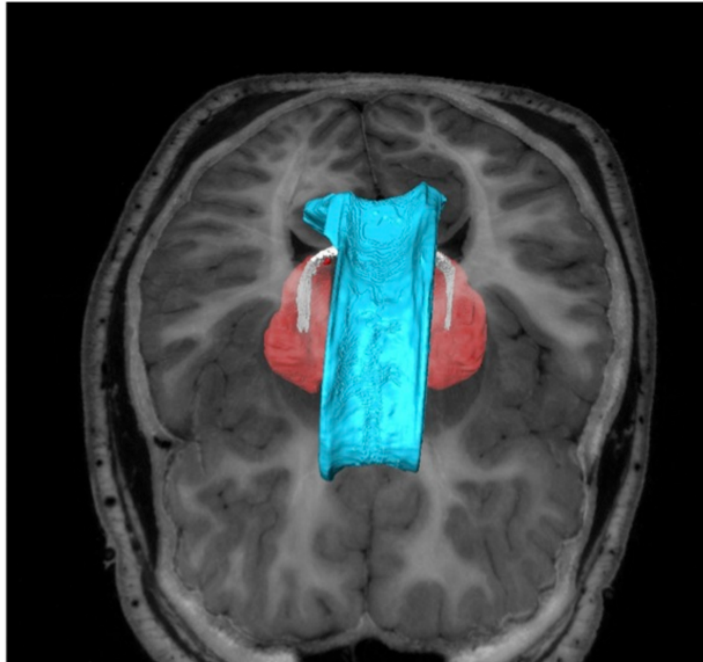




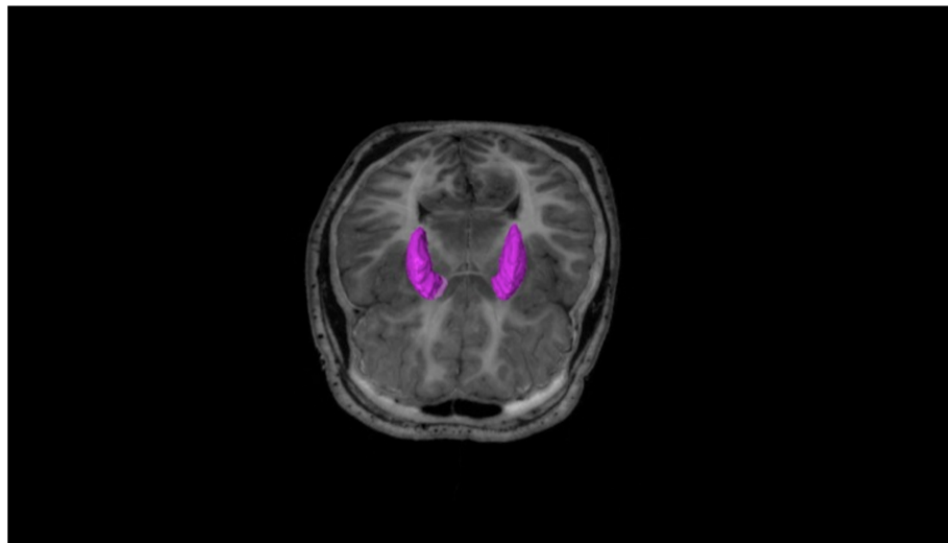
The structure shaded in blue are the .



The hidden structure (not shown) that would be located directly beneath the structure shaded in red is the .



The blue structure seen in the image is known as the



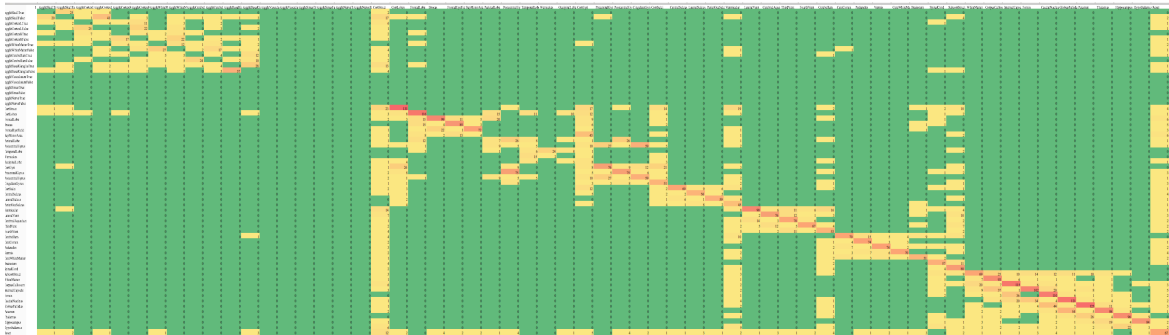
The pink structures seen in the image are known as the



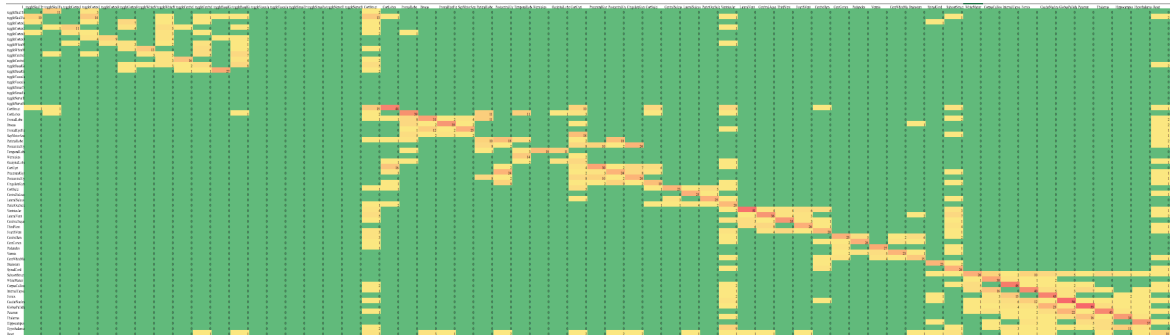
The missing structures (not visible) that are outlined in yellow are the

## Appendix C: Paired-Interaction Frequency Matrices with the 3D E-Learning Resource

Low Spatial Ability Participants' Paired-Interaction Frequency Matrix

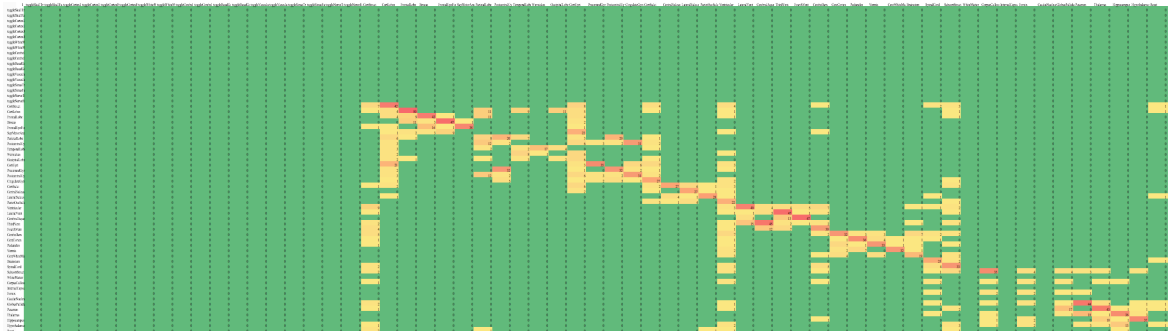


High Spatial Ability Participants' Paired-Interaction Frequency Matrix

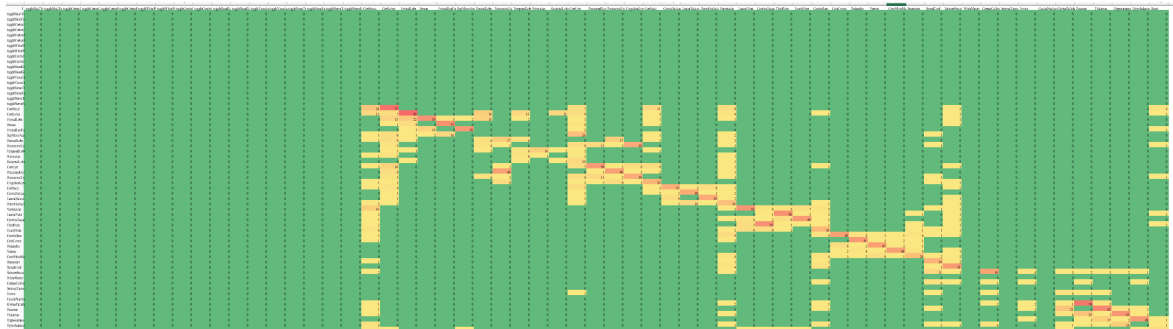


## Appendix D: Paired-Interaction Frequency Matrices with the 2D E-Learning Resource

Low Spatial Ability Participants' Paired-Interaction Frequency Matrix



High Spatial Ability Participants' Paired-Interaction Frequency Matrix



## Appendix E: Copyright Licenses

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Licensed Content Author	Lauren K. Allen,Roy Eagleson,Sandrine de Ribaupierre
Licensed Content Date	Mar 15, 2016
Licensed Content Pages	9
Type of use	Dissertation/Thesis
Requestor type	Author of this Wiley article
Format	Electronic
Portion	Full article
Will you be translating?	No
Title of your thesis / dissertation	TEACHING NEUROANATOMY VIRTUALLY: INTEGRATION OF AN INTERACTIVE 3D E-LEARNING RESOURCE FOR ENHANCED NEUROANATOMY EDUCATION
Expected completion date	Apr 2018
Expected size (number of pages)	180

# Curriculum Vitae

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**Allen LK**, Eagleson, R., de Ribaupierre, S. (2018) *Improving Spatial Neuroanatomy Comprehension: The Impact of a 3D Interactive E-Learning Resource on the Role of Spatial Ability*. Submitted to Medical Education (under review)

**Allen LK**, Eagleson, R., de Ribaupierre, S. (2016) *Development of a web-based 3D module for enhanced neuroanatomy education*. Studies in Health Technologies and Informatics. 220; 5-8.

**Allen LK**, Eagleson, R., de Ribaupierre, S. (2016) *Evaluation of an online 3D interactive resource for undergraduate neuroanatomy education*. Anatomical Sciences Education. 9: 431–439. doi:10.1002/ase.1604

**Allen LK**, Bhattacharyya S, Wilson TD. (2015) *Development of an interactive 3D model of the eye for enhanced learning of the oculomotor system*. Anatomical Sciences Education. 8 (3); 275-282. doi:10.1002/ase.1487.